Pion femtoscopy at NA61/SHINE

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University of Bologna, CosmicAntiNuclei Seminar
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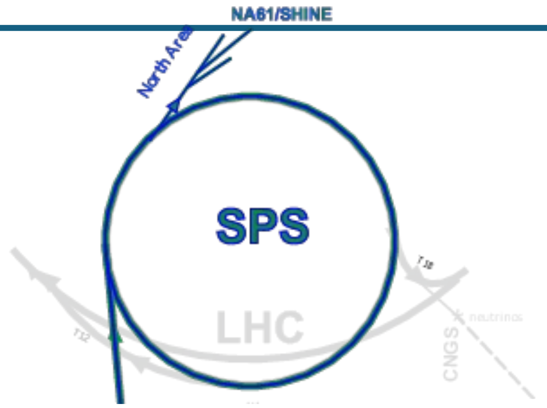
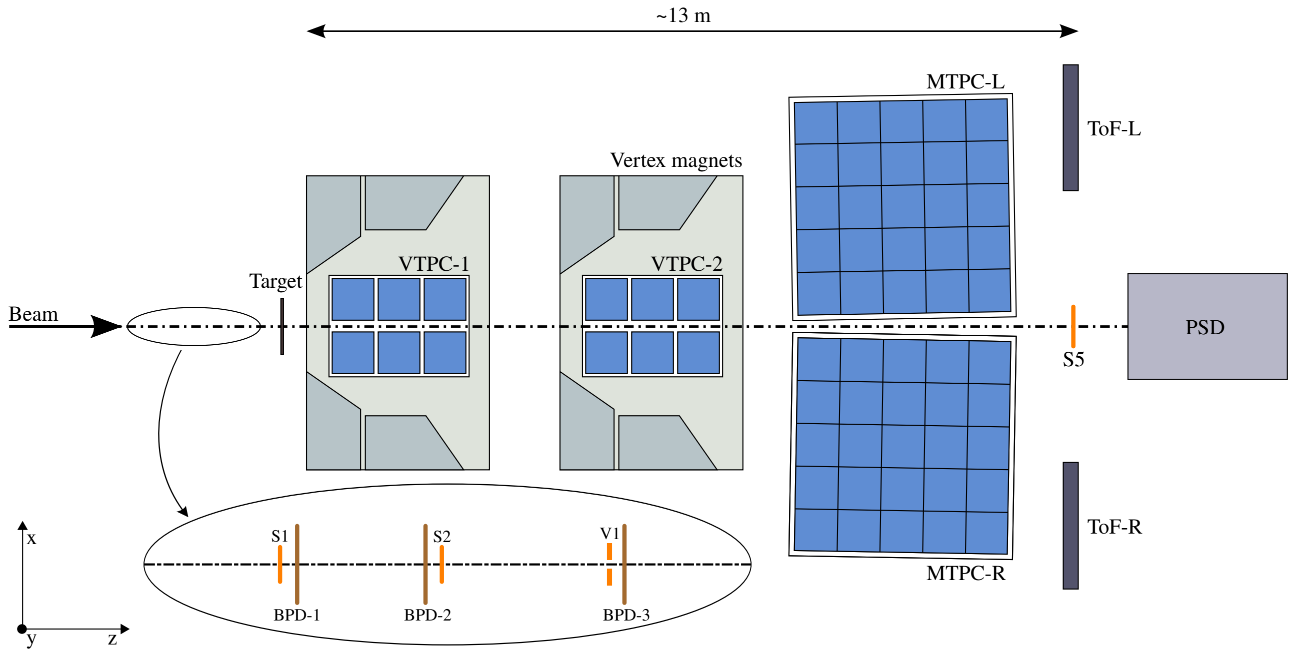
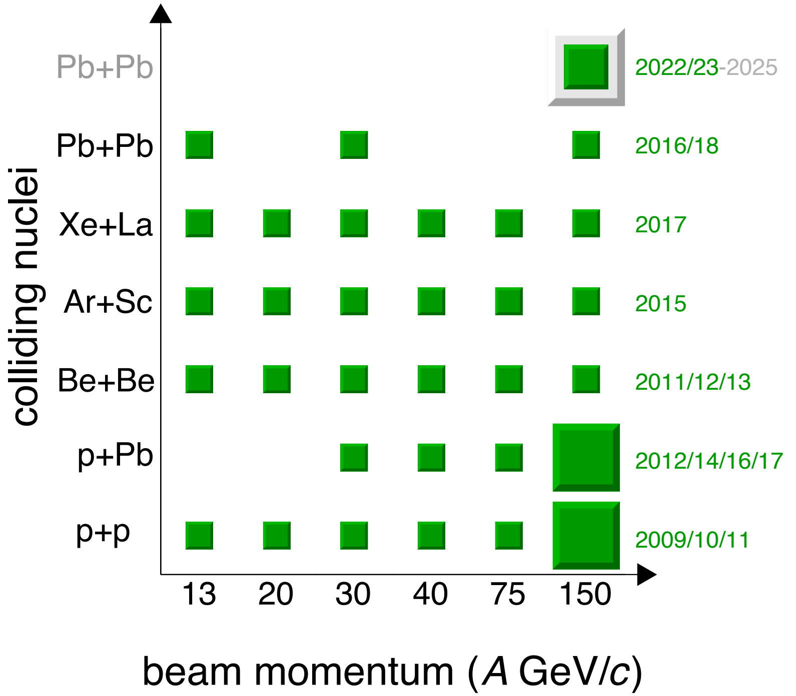
The experiment

- NA61/SHINE, CERN, SPS
  - Strong interaction
  - Neutrino measurements
  - Cosmic ray measurements
- Fixed target
- Various systems, various energies
- After LS2 ~ 20x faster data taking rate (readout from ALICE ☺)





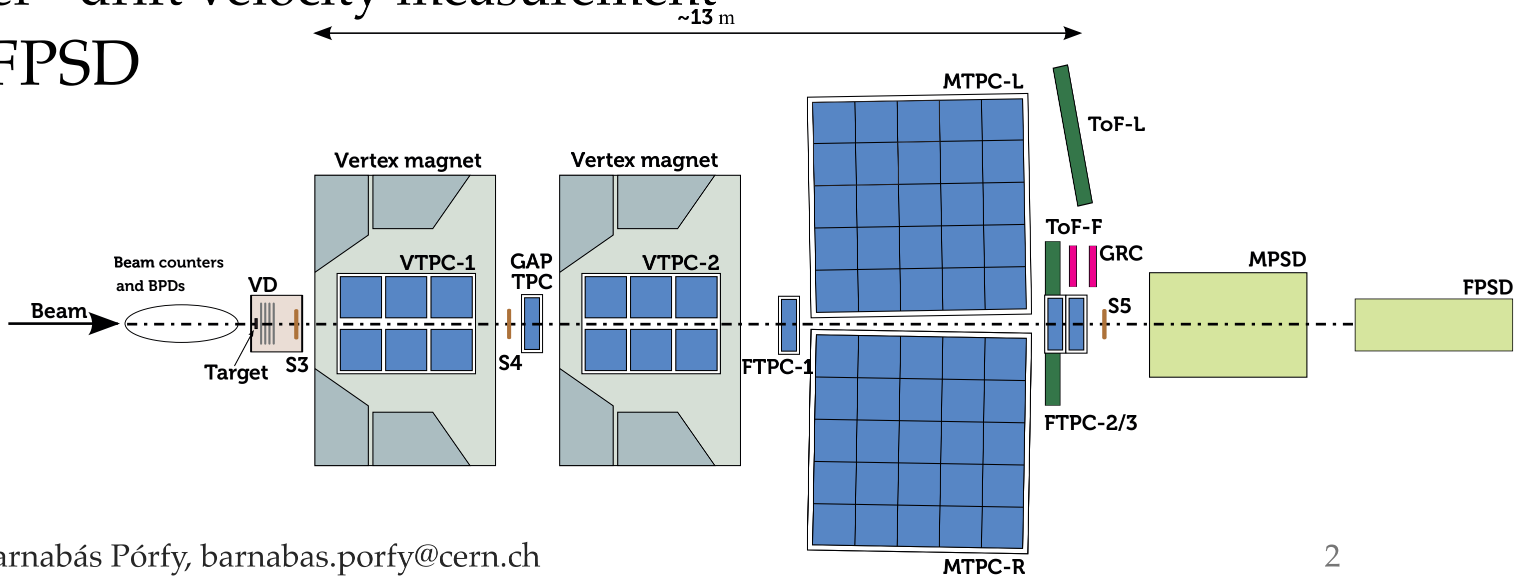
Experiment during Ar+Sc run



$\sqrt{s_{NN}} = 5.3, 6.3, 7.7, 8.8, 11.9, 16.8$

NA61 after the LS2

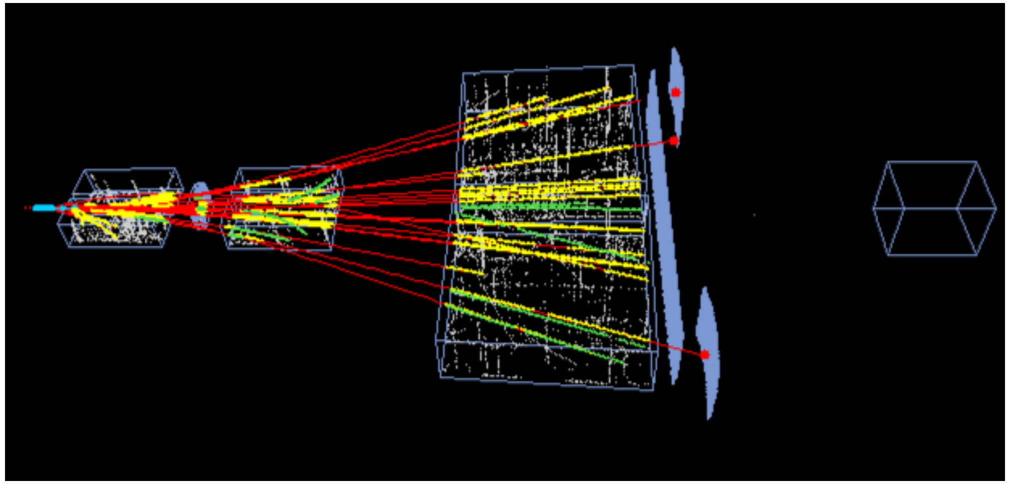
- Upgrade of DAQ + new trigger system (TDAQ)
  - Detector readouts replaced → data taking rate increase 20x
  - TPCs – ALICE (frontends, readout control units); other detectors - DRS4
- Construction of:
  - Vertex Detector - open-charm measurements
  - Long Target Tracker – neutrino program
  - ToF-F wall
  - Multi-gap Resistive Plate Chamber based ToF-L (ToF-R under construction)
  - Beam Position Detector
  - Geometry Reference Chamber - drift velocity measurement
- Upgrade of PSD: MPSD + FPSD

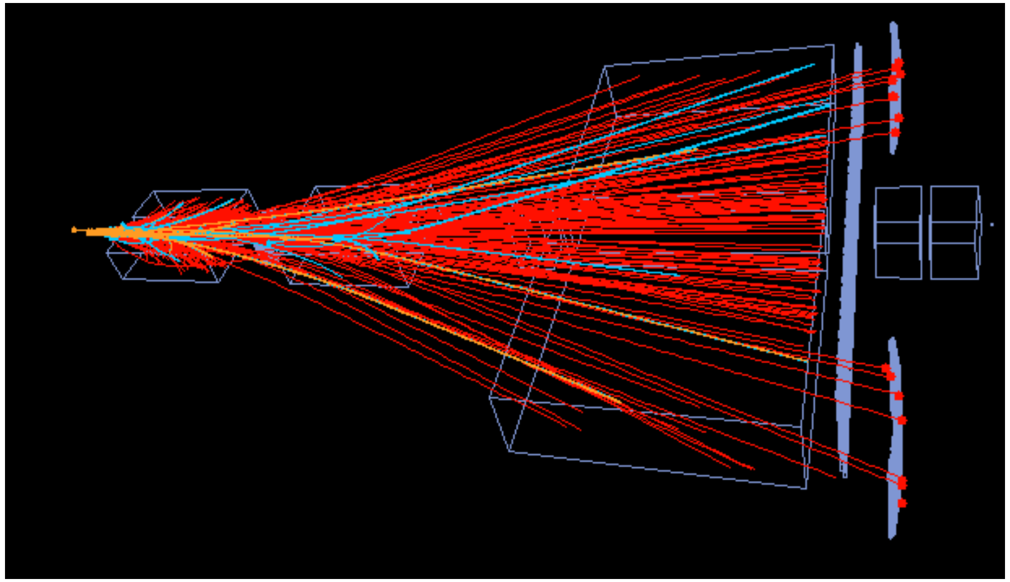


Example event

- Event sample in
  - Be+Be at 150A GeV/c – 2011
  - Ar+Sc at 150A GeV/c – 2015

→ $\sqrt{s_{\mathrm{NN}}} \approx$16.8 GeV
~3M events





Lévy approach – a summary

Based on experimental results: Gaussian not describe data well

Generalized central limit theorem
Lévy distribution (stable, symmetric):

$$\mathcal{L}(\alpha, R; r) = \frac{1}{(2\pi)^3} \int d^3 q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$$

- Generalization of Gauss, power-law$\sim r^{-(d-2+\alpha)}$
- $\alpha = 2$ Gauss, $\alpha = 1$ Cauchy

- Momentum correlation related to source $S(x)$:

$$C(q) \cong 1 + \lambda \cdot \left|\tilde{S}(q)\right|^2$$

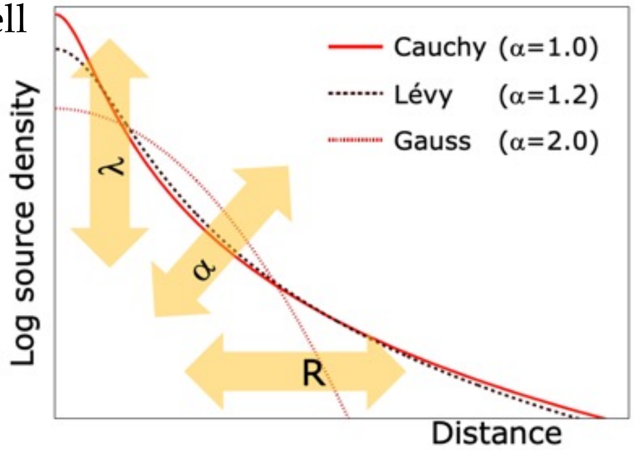
- General approach: Gauss→Lévy shaped source

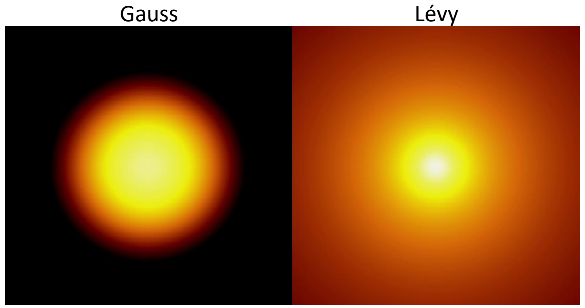
$$C(q) = 1 + \lambda \cdot e^{-(|qR|)^{2\to\alpha}}$$

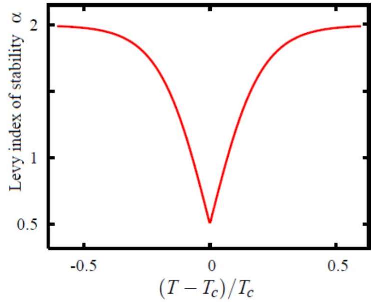
- Actual and mixed pair distribution → $C(q) = \frac{A(q)}{B(q)} \cdot N$
- QCD universality class ↔ 3D Ising

  Halasz et al., Phys.Rev.D58 (1998) 096007,
  Stephanov et al., Phys.Rev.Lett.81 (1998) 4816

- Spatial correlation: $\sim r^{-(d-2+\eta)}$
  Lévy source: $\sim r^{-(d-2+\alpha)}$; $\alpha \Leftrightarrow \eta$?
  Csörgő, Hegyi, Novák, Zajc, AIP Conf. Proc. 828 (2006) 525-532
- At CEP:
  - Random field 3D Ising: $\eta = 0.50 \pm 0.05$
    Rieger, Phys.Rev.B52 (1995) 6659
  - 3D Ising: $\eta = 0.03631(3)$
    El-Showk et al., J.Stat.Phys.157 (4-5): 86



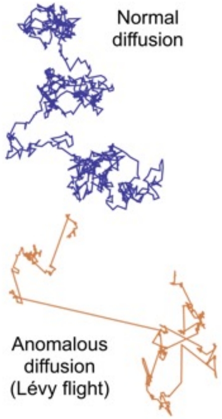




Possible reasons for the appearance of Lévy:

QCD jets; Anomalous diffusion; Critical behavior; ...

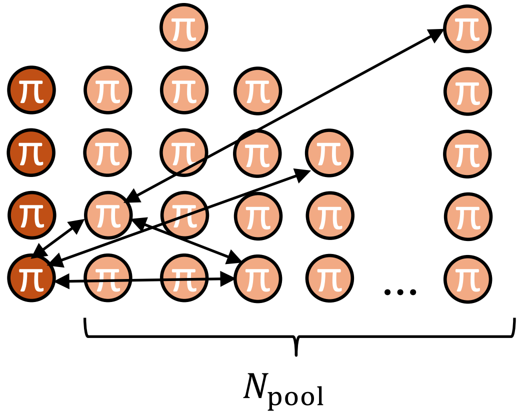
Csörgő, Hegyi, Novák, Zajc, Acta Phys.Polon.B36 (2005) 329-337
Csanád, Csörgő, Nagy, Braz.J.Phys.37 (2007) 1002
Csörgő, Hegyi, Novák, Zajc, AIP Conf.Proc.828 (2006) 525-532
Metzler, Klafter, Physics Reports 339 (2000) 1-77
Kincses, Stefaniak, Csanád, Entropy 24 3 (2022) 308
Kórodi, Kincses, Csanád, Phys.Lett.B 847 (2023)

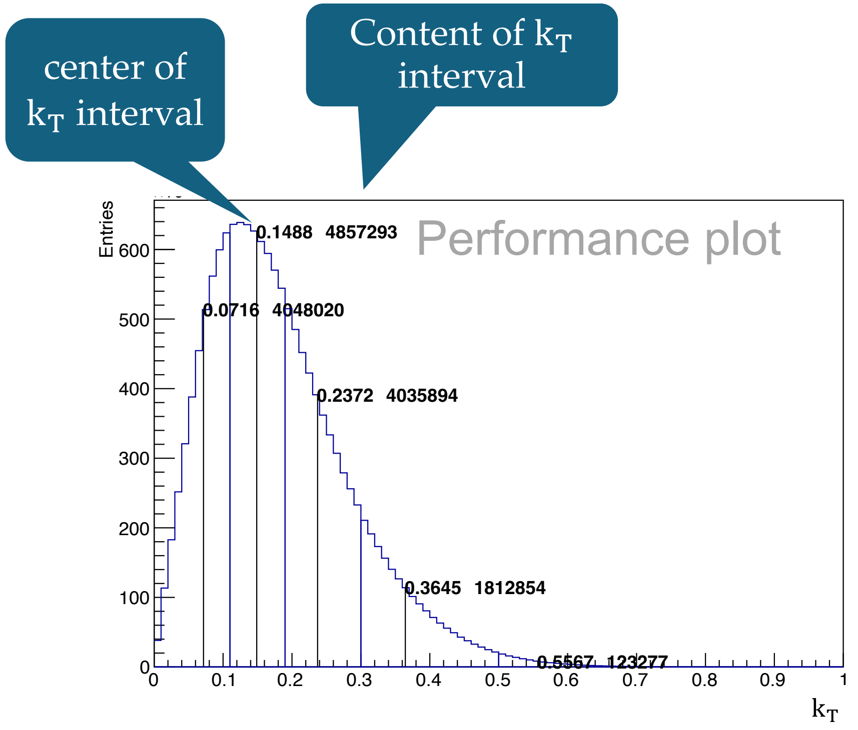


Usual problems, questions

Usual check-list and questions

- 1D or 3D? (Usually decided before…)
- Maximum multiplicity in an event
  - Needed for background mixing
  - Determines size of N_{pool}
- Pair average transverse momenta
  - How large intervals?
  - How many?
  - How should they be distributed?
- Momentum difference variable
  - q_{inv} or q_{LCMS}





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Usual questions – What is the correct variable?

- Correlation function is measured as a function of momentum difference **q**
- Useful to use Longitudinally CoMoving System (Bertsch-Pratt)
  - average momentum orthogonal to beam
  - source is approx. spherically symmetric in nucleus-nucleus collision

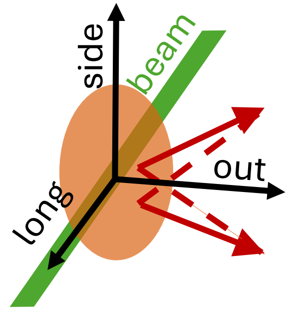
S. Pratt, Phys. Rev. D33, 72 (1986)
G. Bertsch, M. Gong, M. Tohyama, Phys. Rev. C37, 1896 (1988)

- In cases where statistics is not enough: use 1D momentum difference
- Need to check two options: q_{LCMS} or q_{inv} (=PCMS)
- $q_{\mathrm{inv}} = \sqrt{-(E_1 - E_2)^2 + (p_{1x} - p_{2x})^2 + \left(p_{1y} - p_{2y}\right)^2 + (p_{1z} - p_{2z})^2}$

BUT! $q_{\mathrm{inv}} = q_{\mathrm{out}}^2(1-\beta_{\mathrm{T}})^2 + q_{\mathrm{side}}^2 + q_{\mathrm{long}}^2$ ⟶ even if q_{out} is large and $\beta_{\mathrm{T}} \approx 0 \rightarrow q_{\mathrm{inv}}$ can be small! $\beta_{\mathrm{T}} = \frac{K_{\mathrm{T}}}{K_0}$

This makes q observer (q_{LCMS} or q_{inv}) dependent

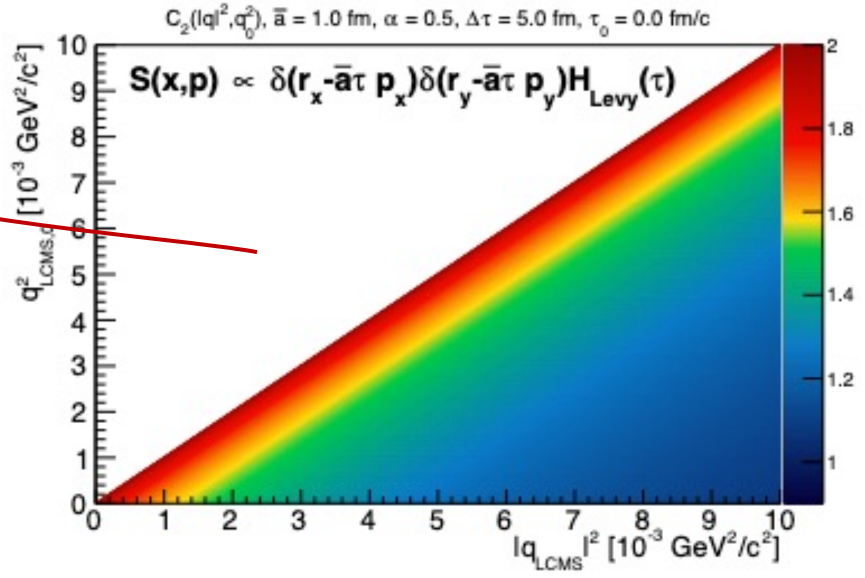
- Can we decide which option is best…?

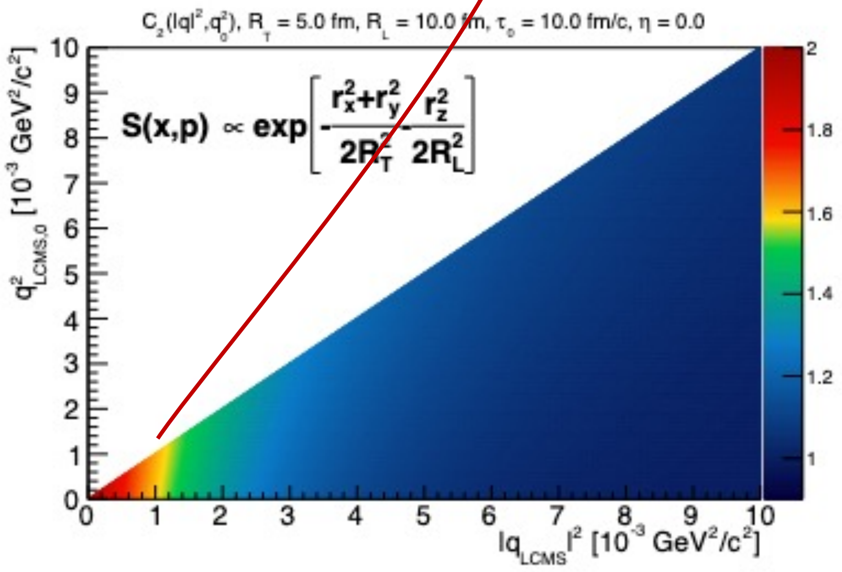


Usual questions – What is the correct variable?

- Yes! We can measure $q_0 = |E_1 - E_2|$ vs. $|\boldsymbol{q}|$
- In case q_{inv} is the correct variable, we expect maximum diagonally
- In case q_{LCMS} is the correct variable, we expect maximum near 0
- $|\boldsymbol{q}_{\mathrm{LCMS}}| = \sqrt{(p_{1x} - p_{2x})^2 + \left(p_{1y} - p_{2y}\right)^2 + q_{z,\mathrm{LCMS}}^2}$

$$q_{z,\mathrm{LCMS}}^2 = \frac{4(p_{1z}E_2 - p_{2z}E_1)^2}{(E_1+E_2)^2 - (p_{1z}+p_{2z})^2}$$





Cuts and usual problems

Usual cuts

- Centrality selection
  - statistics, compatibility with other data
- How to mix the events
- Rapidity cut (around midrapidity)
- PID
  - Bethe Bloch and/or ToF?
  - Pions, kaons, protons?
- Track splitting
  - visible spike in actual pair distribution
- Track merging
  - visible in pair distance (geometrical, momentum space,...)
- Fitting range
  - where to start and where to finish

(Two-particle) femtoscopy measurement steps

After the good tracks are selected… create:

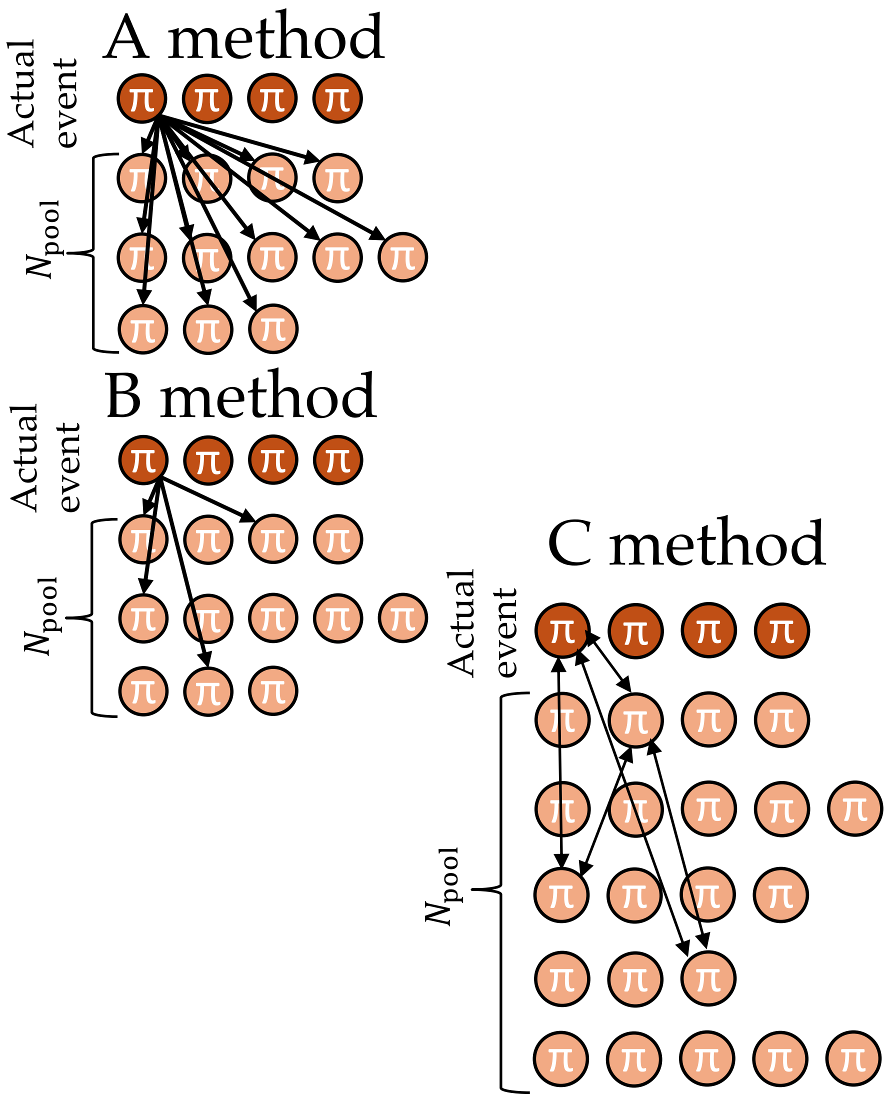
- $A(q)$: Actual event relative momentum distribution
  - pairs from same event
- $B(q)$: Background event relative momentum distribution
  - pairs from mixed event
- $C(q) = A(q)/B(q) \cdot \mathcal{N}$
- Measure $C(q)$ for various m_T bins
  - m_T = average transverse mass of the pairs
- Fit $C(q)$ with suitable function
- Determine m_T dependence of fit parameters

$$m_\mathrm{T} \equiv \sqrt{m_\pi^2 + k_\mathrm{T}^2}$$

Event mixing

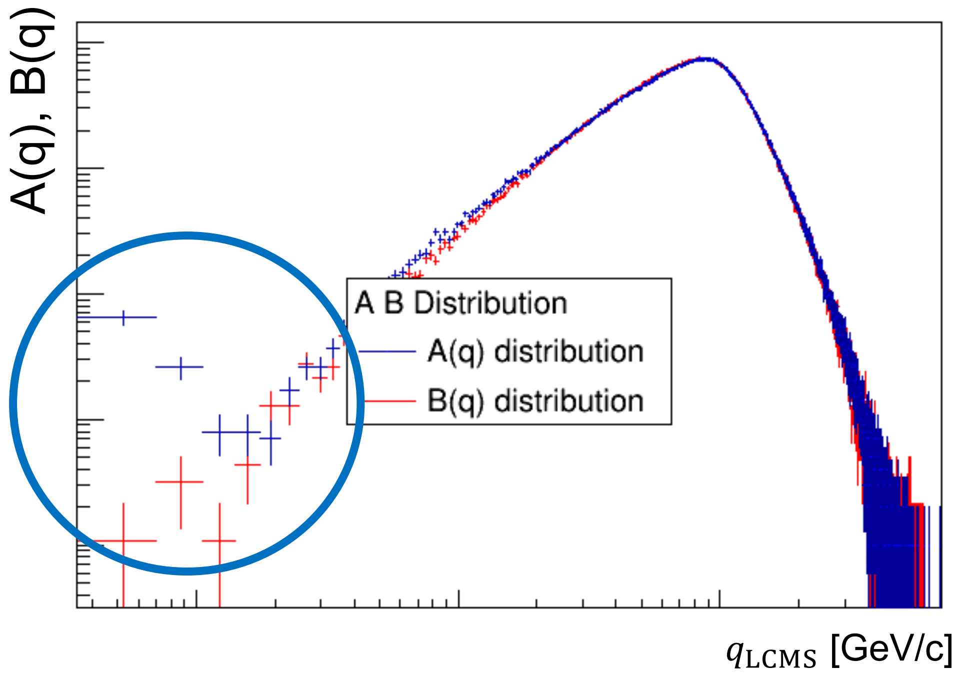
General idea: fill up N_{pool} events from previous actual events, in different classes – centrality, multiplicity,…

- Actual/current event with n pions
- **A method**: make pairs with all pions of the pool to all actual pions
- **B method**: make pairs with all actual pions to a random selection of n background pions
- **C method**: select randomly one event and select randomly one pion, make pairs
- In our (and most) case, C method is preferred and used

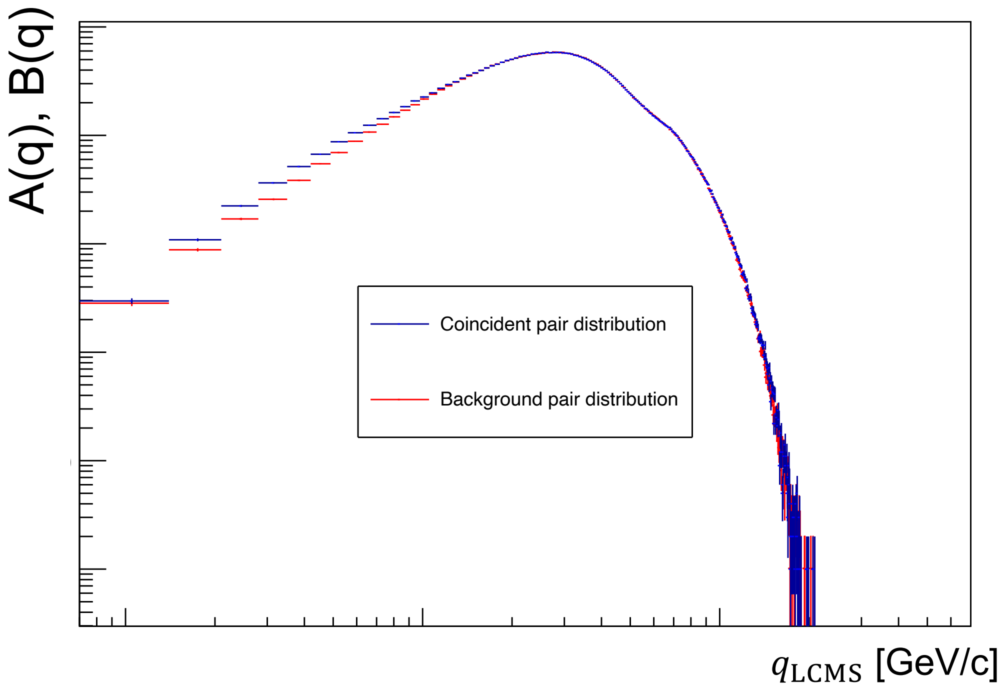


A-B and track splitting

- Track splitting spike in low-q is a telling sign in A(q), B(q)

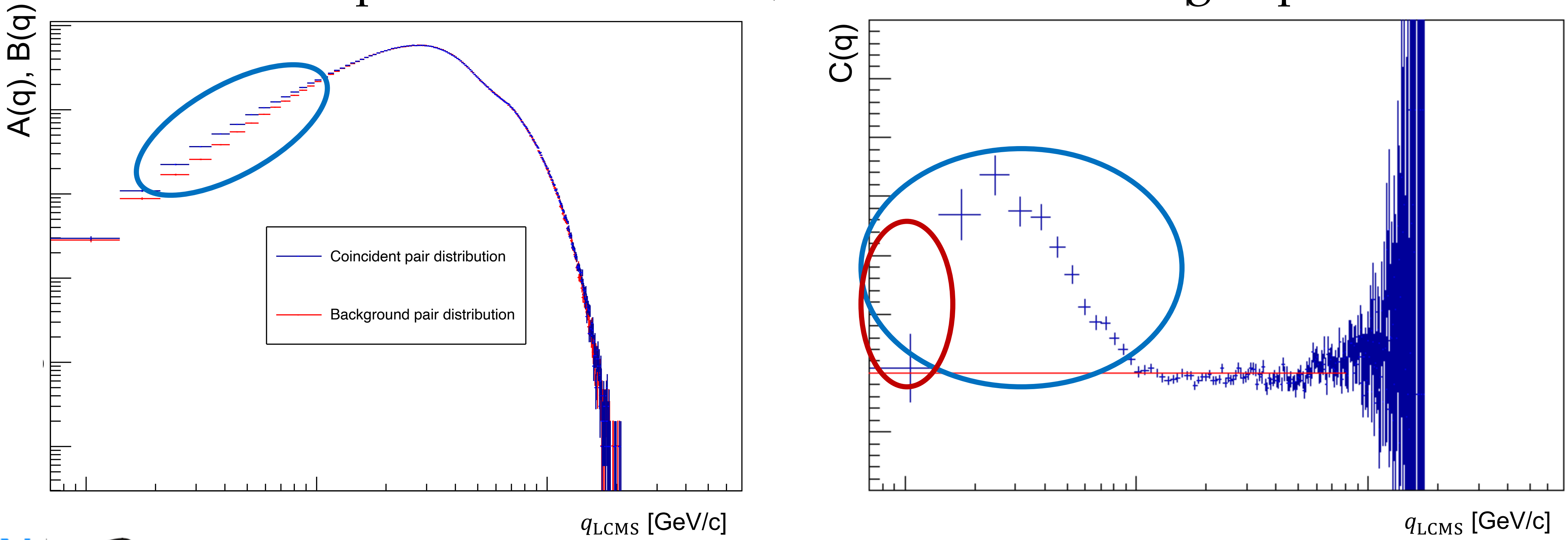


After applying selection for track splitting



A healthy A-B-C

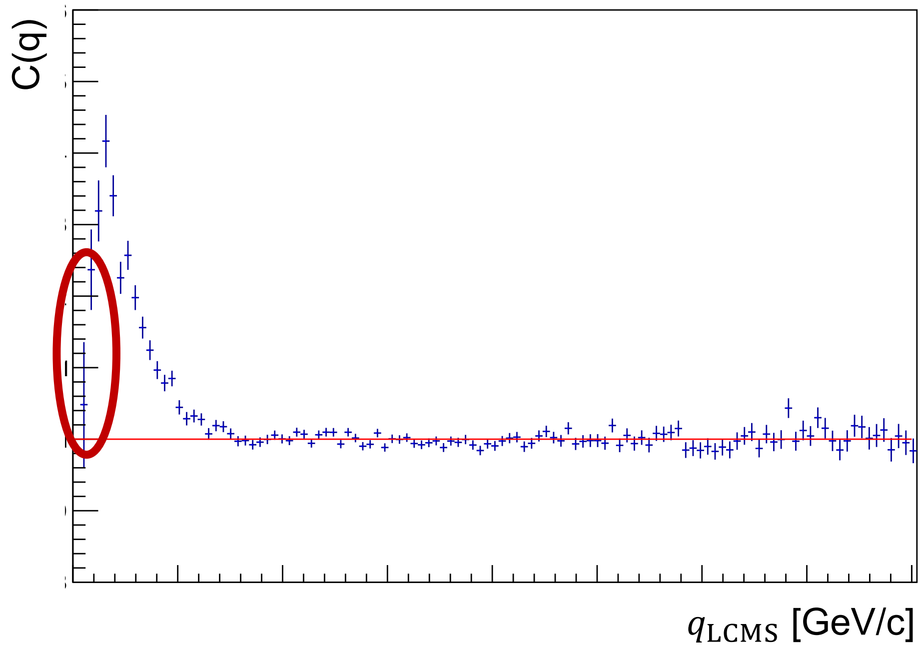
- Example plots of A(q), B(q), C(q)
- B-E effect visible in blue circle
- Coulomb repulsion in red circle, in case of like charged pairs

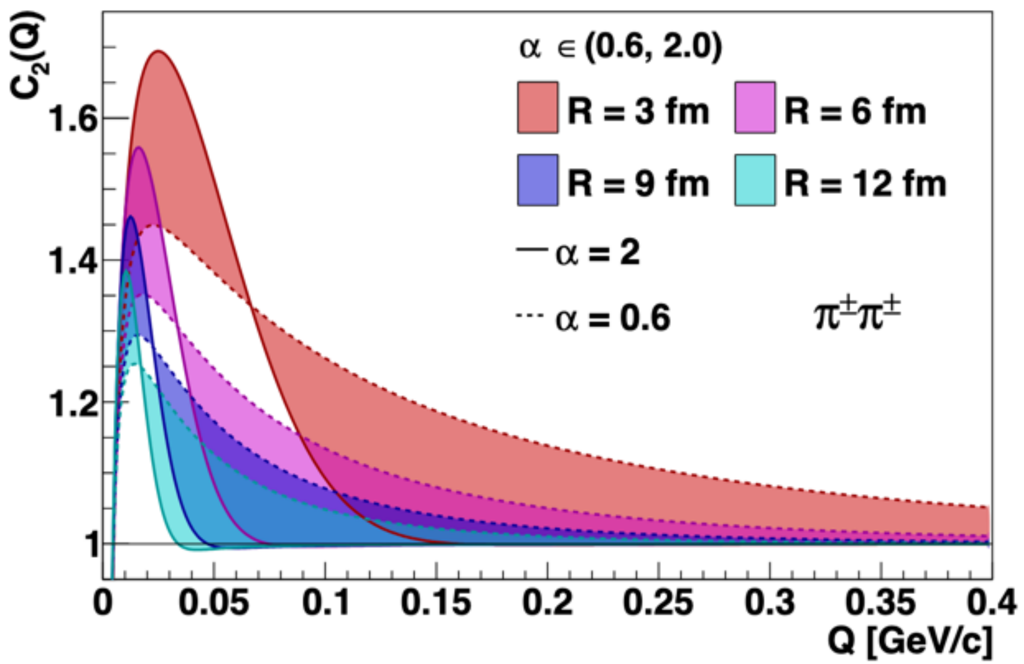


Coulomb correction

- Dealing with like charged pairs → Coulomb repulsion
- Coulomb correction is needed (CC)
- Calculation is possible via a novel method of numerical integration
- Plug-n-play tool available: https://github.com/csanadm/CoulCorrLevyIntegral

Nagy, M., Purzsa, A., Csanád, M. and Kincses, Dániel, Eur.Phys.J.C 83 (2023) 11, 1015





Coulomb correction „correction”

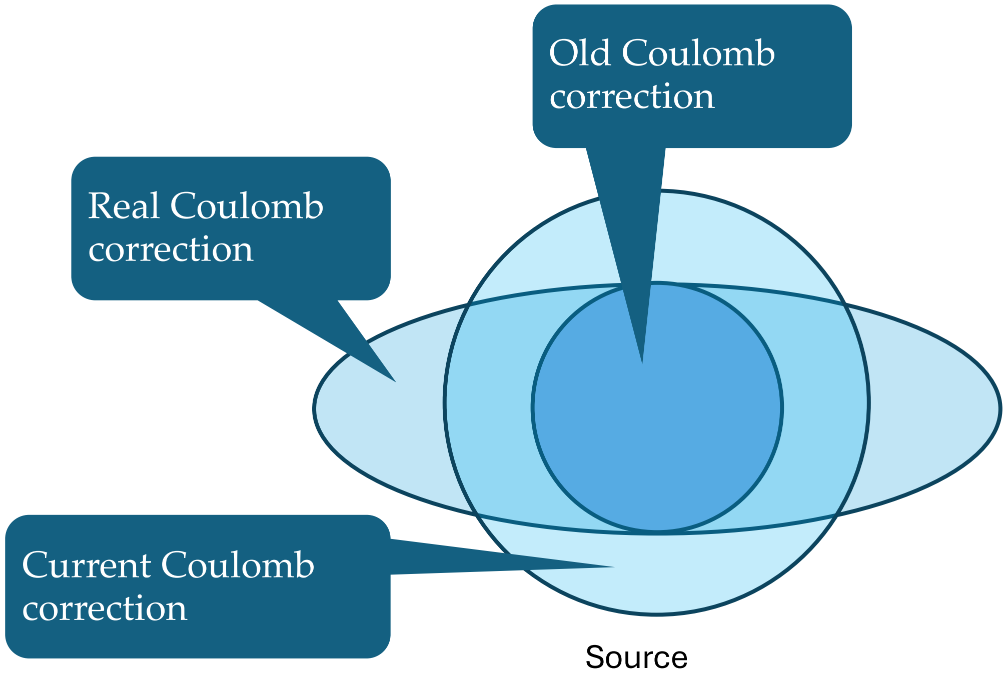
- Measuring in LCMS, but Coulomb correction is in PCMS
- This is negligible, but 1D spherical source in LCMS
  NOT spherical in PCMS
- Boost R to PCMS: $R_{PCMS} = \sqrt{\frac{1-\frac{2}{3}\beta_T^2}{1-\beta_T^2}} \cdot R$
  where $\beta_T = \frac{K_T}{m_T}$

$$q_{inv} \approx \sqrt{1-\beta_T^{\frac{2}{3}}} \cdot q_{LCMS}$$

$$K_{Coul}(q,R) = K_{Coul}\left(\sqrt{1-\beta_T^{\frac{2}{3}}} \cdot q, \sqrt{\frac{1-\frac{2}{3}\beta_T^2}{1-\beta_T^2}} \cdot R\right)$$

Use this source for Coulomb correction

- Old Coulomb correction: fits into the source
  - smaller in size
- Current Coulomb correction: same size
  - smaller in longitudinal
  - larger in transversal



B. Kurgyis, D. Kincses, M. Nagy, and M. Csanád, Universe 2023, 9(7), 328

Fitting with Lévy parametrization

M. Nagy, A. Purzsa, M. Csanád, D. Kincses
Eur. Phys. J. C 83, 1015 (2023)

- Formula without final state interactions:

$$C^0(q) = 1 + \lambda \cdot e^{-(|qR|)^{\alpha}}$$

LCMS momentum difference

$$q = |\boldsymbol{q}_{LCMS}| = \sqrt{(p_{1x} - p_{2x})^2 + (p_{1y} - p_{2y})^2 + q^2_{long,LCMS}}$$

Coulomb correction:

$$K_{\mathrm{Coul}}(q;\alpha,R) = \frac{C_2^{\mathrm{Coulomb}}(q)}{C_2^0(q)}$$

FSI free

- Fitting formula, Bowler- Sinyukov:

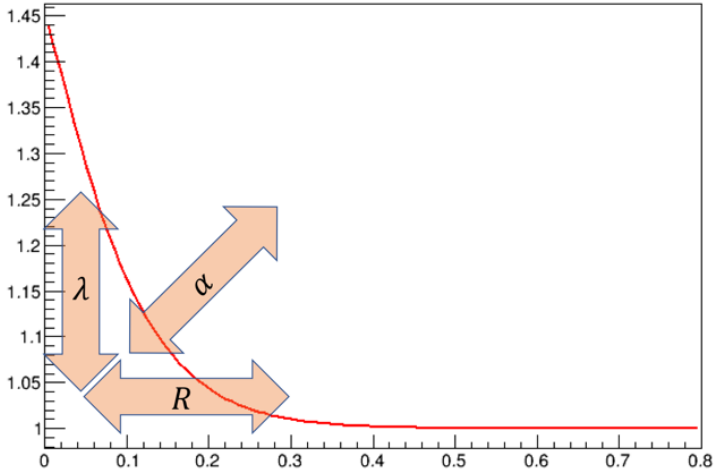
Yu. Sinyukov et al., Phys. Lett. B432 (1998) 248,
M.G. Bowler, Phys. Lett. B270 (1991) 69

$$C(q) = N \cdot \left(1 - \lambda + \left(1 + e^{-(qR)^{\alpha}}\right) \cdot \lambda \cdot K_{\mathrm{Coul}}(q)\right) \cdot (1 + \varepsilon q)$$

N – normalization, ε – background linearity

- Physics parameters
  - λ: correlation strength (core/halo model)
  - R: Lévy scale parameter (similar to HBT size, ~length of homogeneity)
  - α: Lévy index (CEP proximity, shape of the source):

Core-halo model:
Csörgő, Lörstad, Zimányi, Z.Phys.C71 (1996)
Bolz et al, Phys.Rev. D47 (1993) 3860-3870

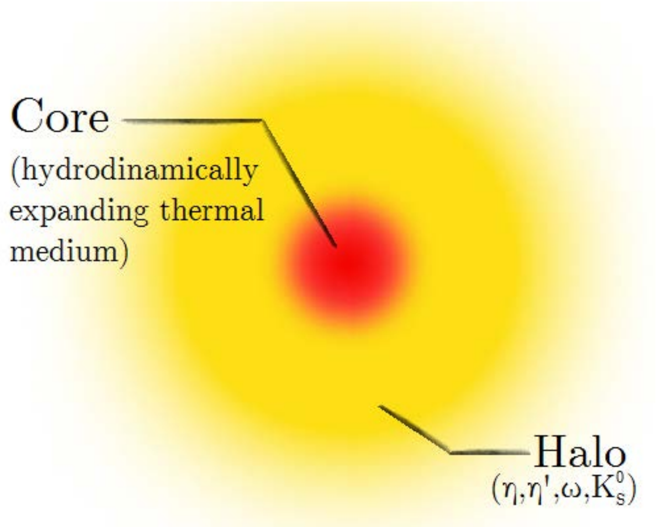


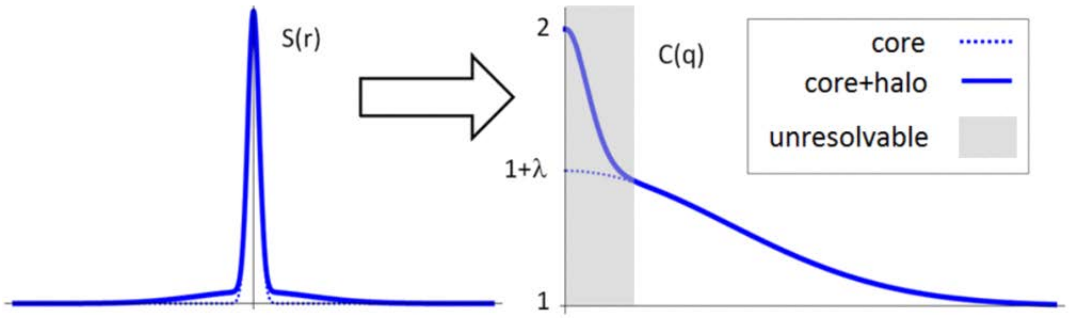
Core-halo model

- Hydrodynamically increasing core → pion emission
- Results in two-component core + halo source:

$$S(x) = S_{\text{core}}(x) + S_{\text{halo}}(x)$$

- Core: thermal hydro medium, size $\lesssim 10$ fm
- Halo: long lived resonances $(\omega, \eta, K_0^S, \ldots)$, size $\gtrsim 50$ fm
- Halo is not seen due to detector resolution
- Real $q \to 0$, at $C(q = 0) = 2$
- Experimentally: $C(q \to 0) \to 1 + \lambda$
  - Experimentally $q \lesssim 5 - 10$ MeV/c not accessible
  - Halo size "corresponds" to small momenta
  - Define $\lambda = \left(\frac{N_{\text{core}}}{N_{\text{core}} + N_{\text{halo}}}\right)^2$





Fitting and fitting ranges

- Goodness-of-fit: χ^2, NDF → confidence level

#1 rule: good fit should have CL > 0.01%

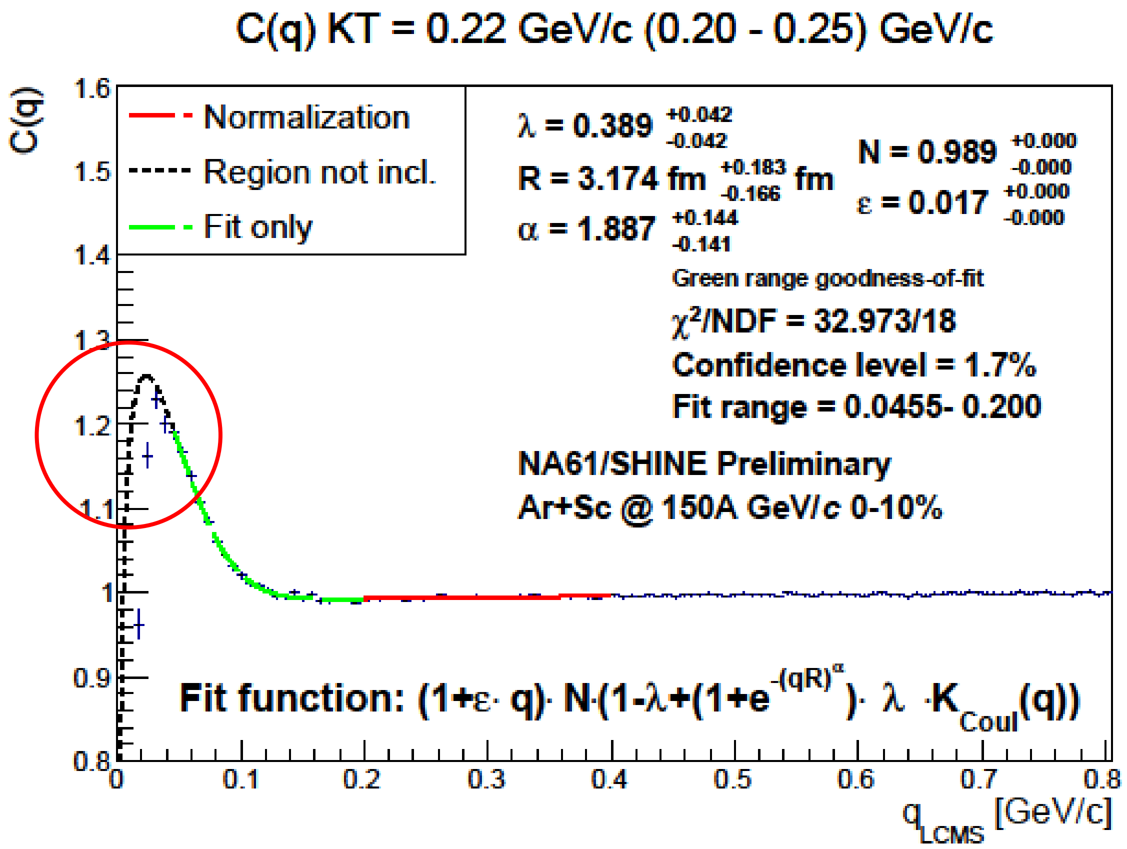
  - Below that, it shouldn't be accepted

- Fit ranges start and end of fit (q_{min}, q_{max}) must be optimized
  - Select by eye q_{max} where C(q) is "flat" already
  - Performing fit with q_{min} steps bin-by-bin
    starting point of the scan can be around B-E peak
    ending point of the scan can be around middle to end of the B-E slope
  - Display all obtained parameters with values, error bars + highlight if fit failed
- How to select fit ranges? All below should be considered simultaneously
  - Fit converged
  - Parameter values are believable ($\alpha \ngtr 2$, $\lambda \ngeq 1$)
  - Trend of parameters
  - Generally, fit q_{min} should increase with increasing K_T bins

Takes ~50% (or more ☺) of total work

Low-q range issue – MC correction?

- Low-*q* range – fits overestimate the data
  - Experimental artefact?
- Maybe use Monte Carlo to correct this effect?



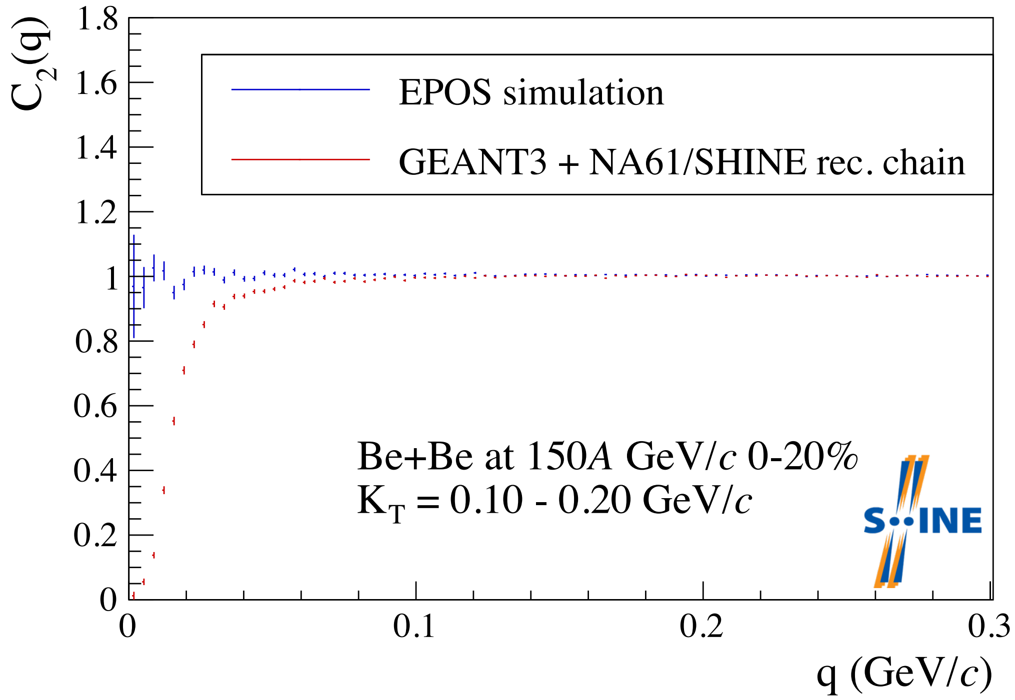
Monte Carlo correction idea

- Correction is possible via:

$$R_{\text{paireff}} = \frac{C_{\text{rec}}}{C_{\text{sim}}} \rightarrow C(q)/R_{\text{paireff}}$$

- Correction is unstable

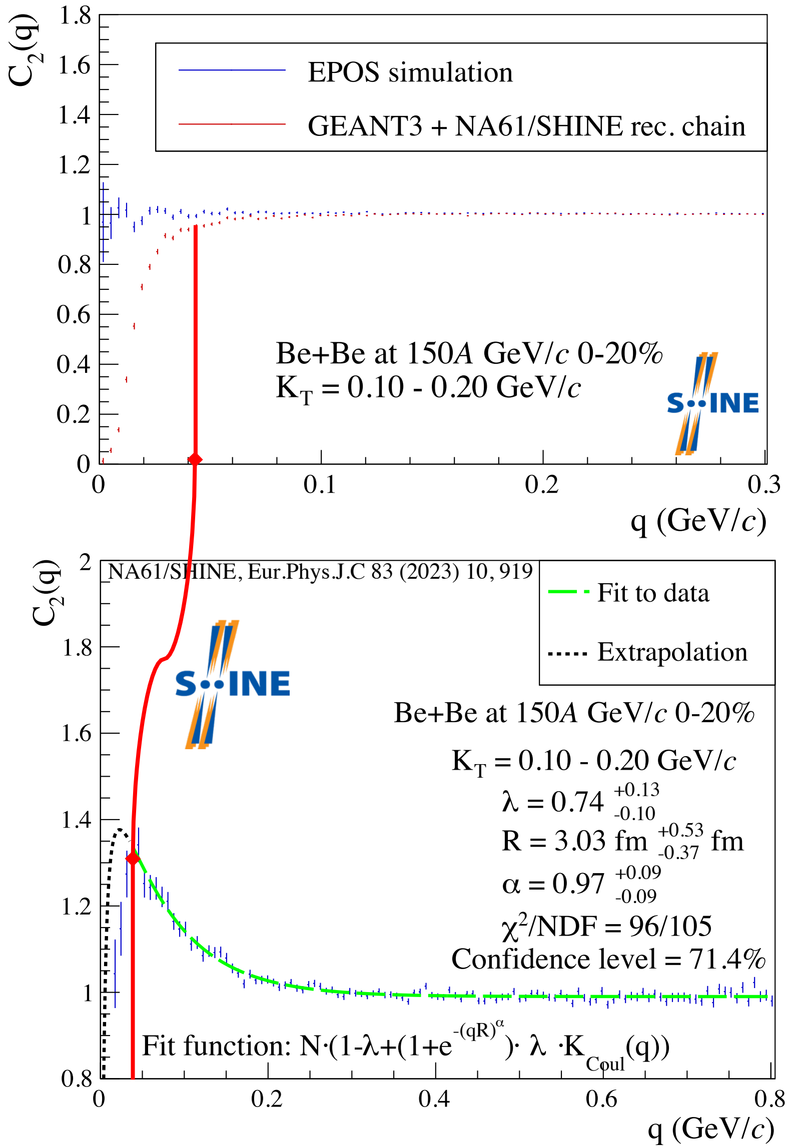
OK, then what can we use it for?



Monte Carlo estimation

We can estimate the start of this strong cutoff

- B-E and Coul. effect not present in EPOS simulation
  - $C_2(q) \approx$ const.
- Low-q range behavior in data:
  - Fits overestimate data
  - Theoretical correlation function cannot describe
  - Observed in Be+Be, Ar+Sc
- Strong cutoff observable
  - Several possibilities...
  - Might be experimental artefact?
- Visible deviation from generated (simulated)
  - Effects such as track merging present
- Low-q region (until reco. ≈ 1) can be excluded
  - Two Track Distance (track merging) cut not used

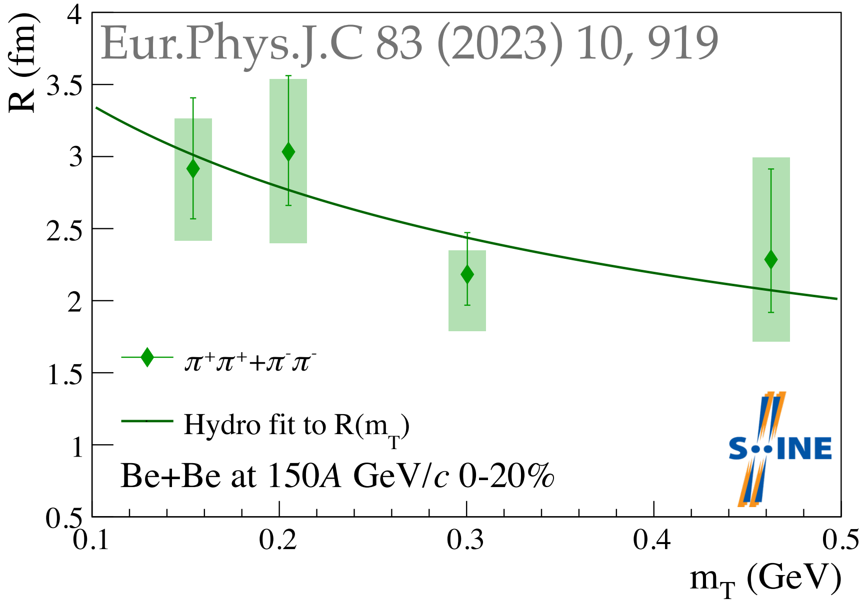


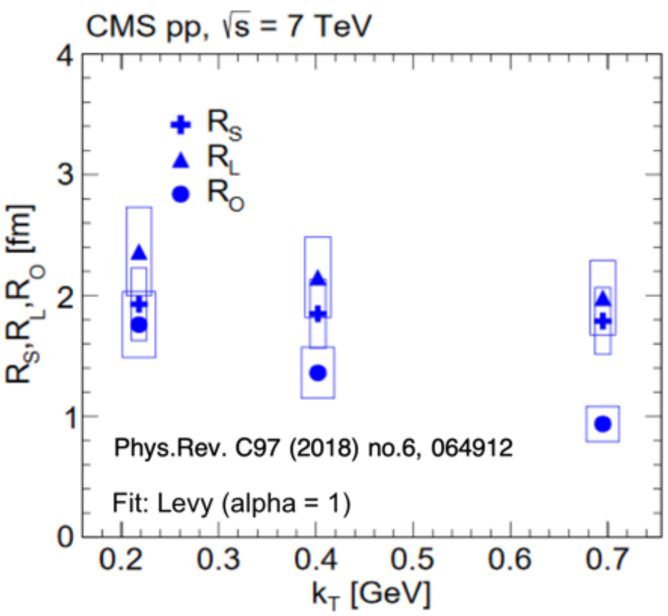
^{7}Be+^{9}Be at highest energy

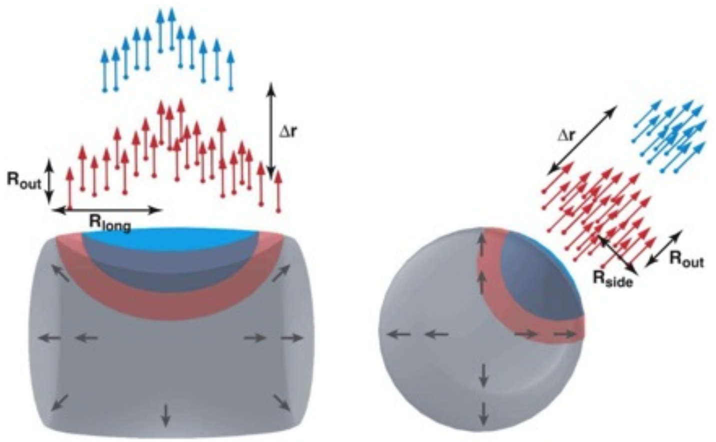
$$m_T \equiv \sqrt{m_\pi^2 + k_T^2},\ k_T \equiv 0.5\sqrt{k_x^2 + k_y^2}$$

- Lévy scale parameter R – related to length of homogeneity
  - Region in space
  - Emission of particles are coherent, correlated
- System size comparable to p+p
- R decreasing trend, $\frac{1}{R^2} \propto m_T$ (calculated for Gaussian shape!)

Csörgő, Lörstad, Phys.Rev.C54 (1996) 1390







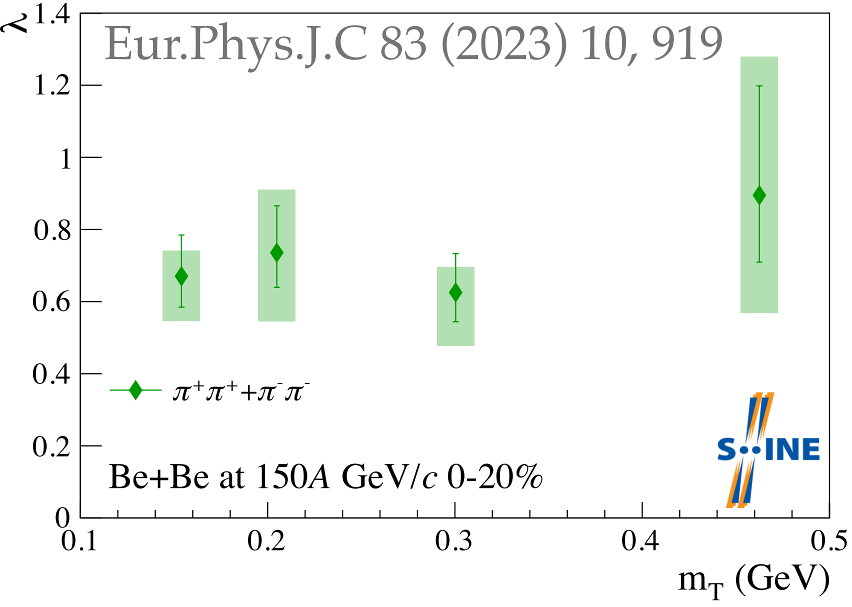
^{7}Be+^{9}Be at highest energy

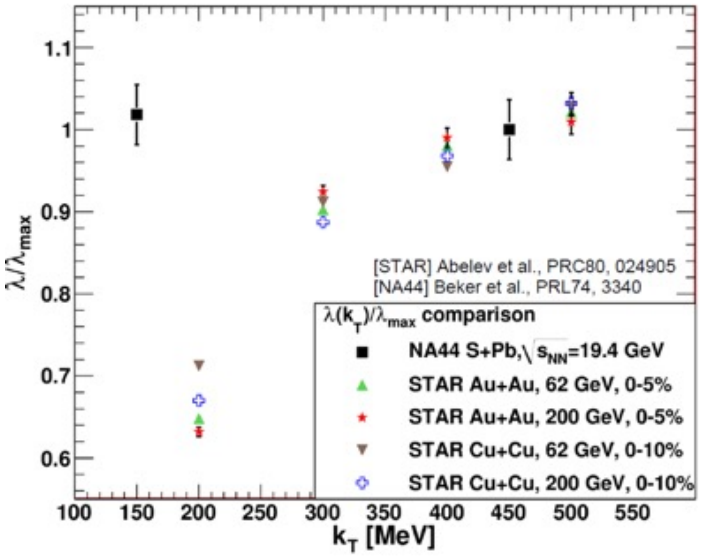
- Correlation strength / intercept parameter λ
  - Related to the core-halo model
- Small size ~ p+p
- λ ~ constant, no decrease with low m_T
- Compared to STAR, PHENIX: lack of decrease at low-m_T

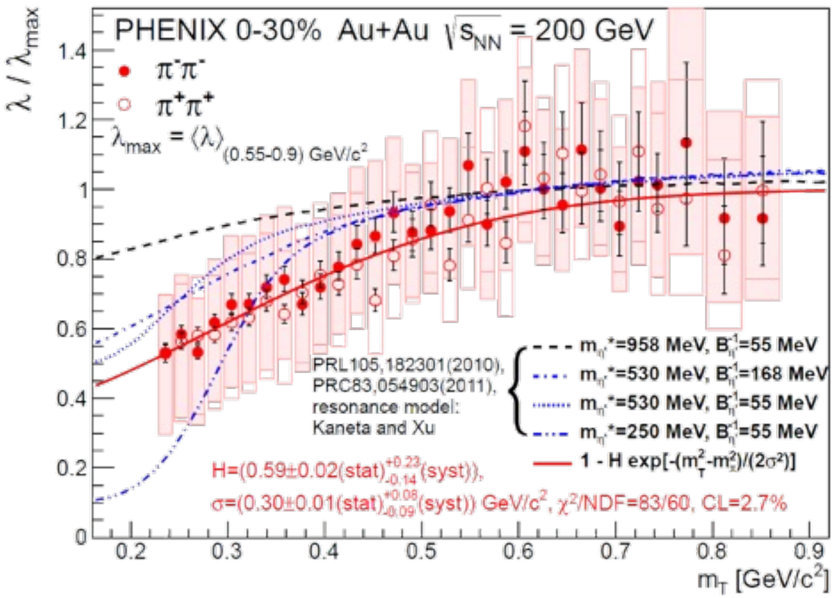
Possible explanation for increasing N_{halo}:

- In-medium-mass modification of η'
  - Large mass due to chiral symmetry breaking
  - Potential chiral symmetry restoration→ lower mass
  - Lower mass → more produced → larger halo

Kapusta, Kharzeev, McLerran, PRD53 (1996) 5028
Vance, Csörgő, Kharzeev, PRL 81 (1998) 2205
Csörgő, Vértesi, Sziklai, PRL105 (2010) 182301
PHENIX, Phys.Rev. C97 (2018) no.6, 064911

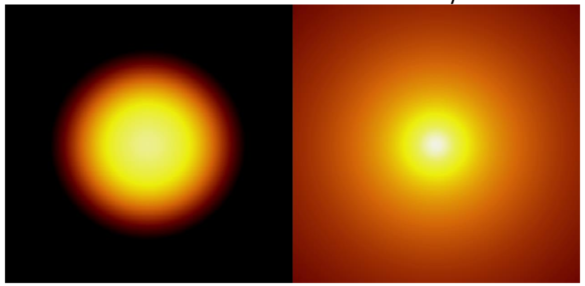


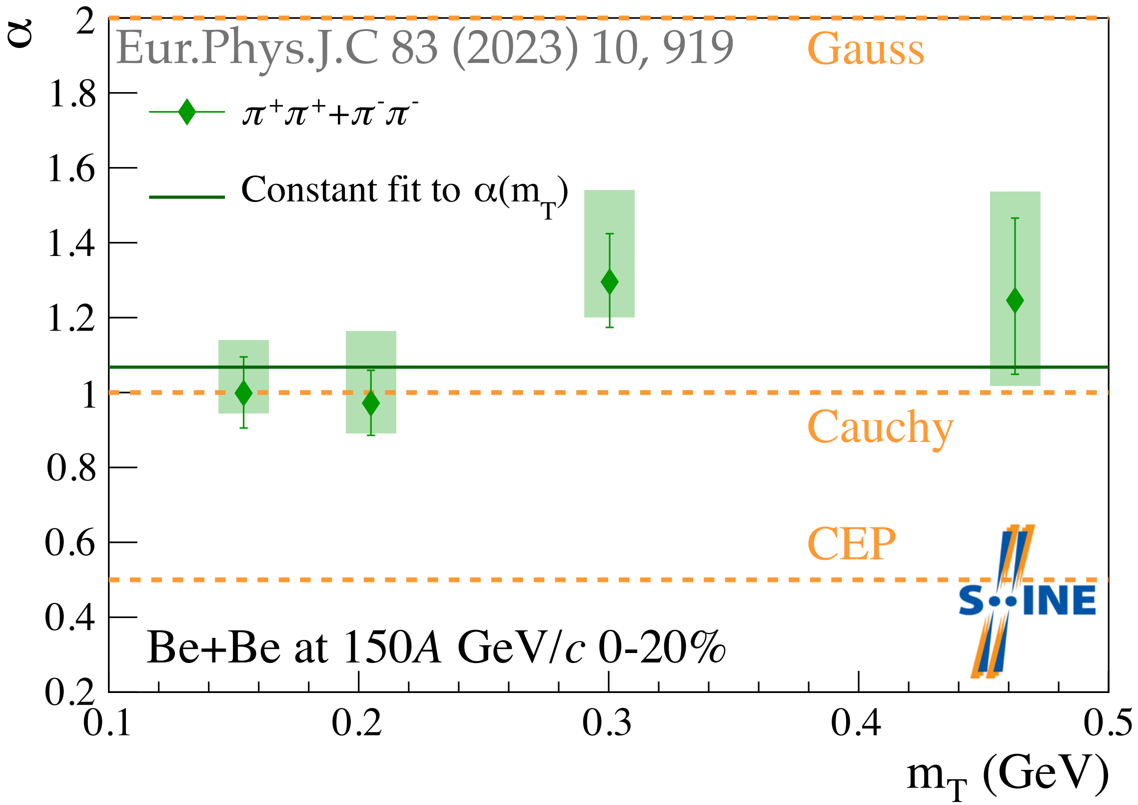




^{7}Be+^{9}Be at highest energy

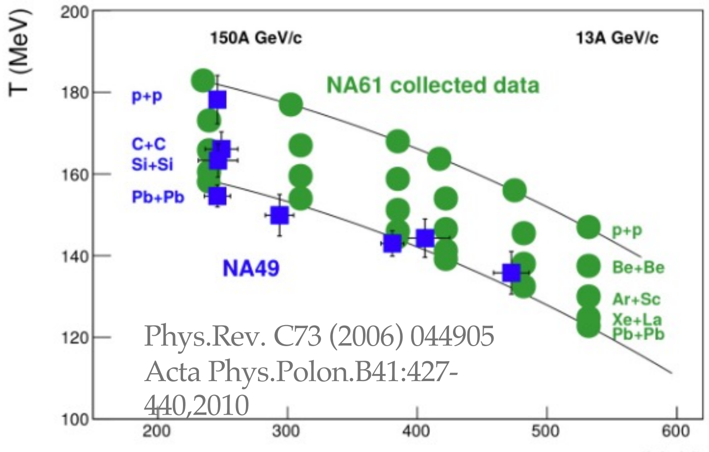
- Lévy stability index α: shape of spatial correlation
- Small system, comparable to p+p
- $\alpha \approx 1 \rightarrow$Cauchy shape, $\neq$ Gauss, $\neq$ CEP
- Compatible with Lévy assumption

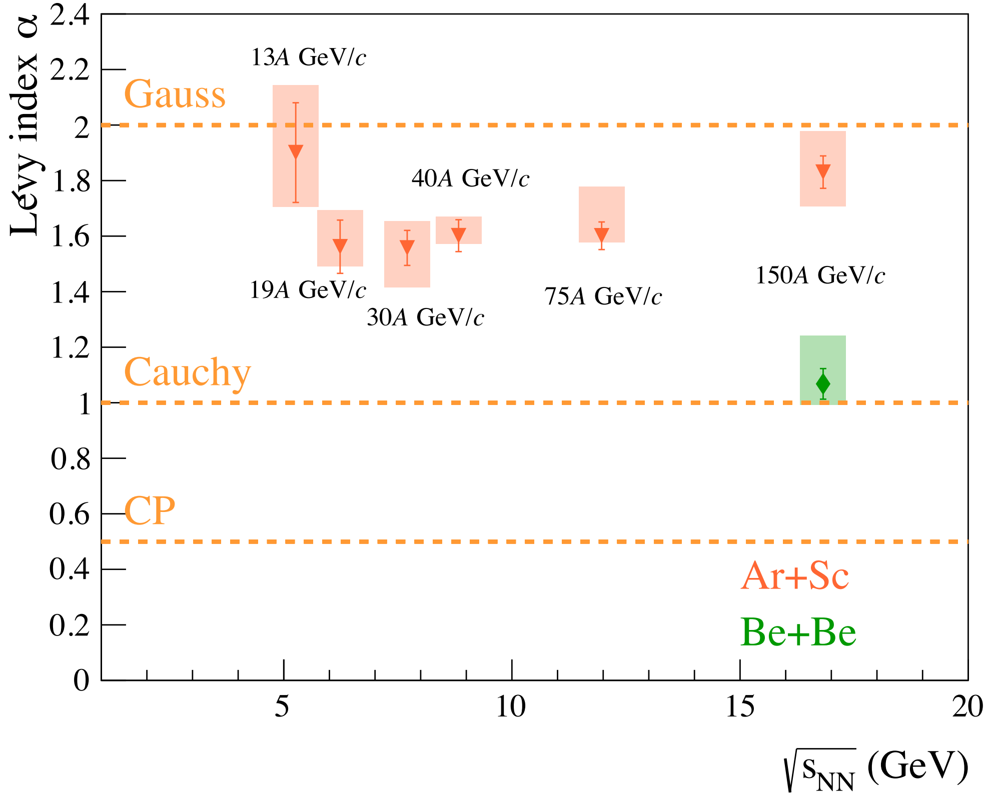


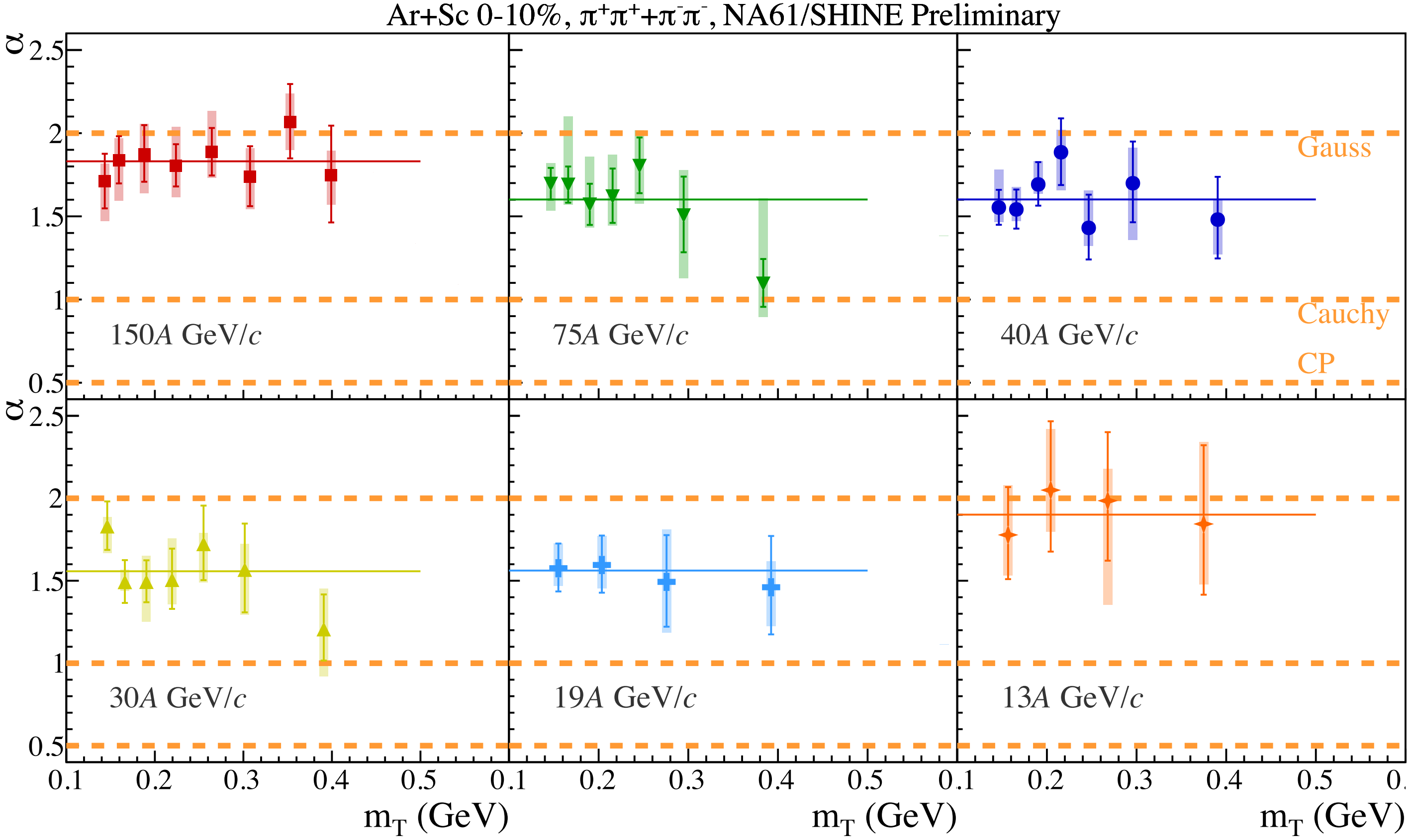


Energy dependence in ^{40}Ar+^{45}Sc

- Different energies, different T, μ_B
- Interesting trend: $\sim \sqrt{s_{NN}} = 6 - 8$ GeV minimum?





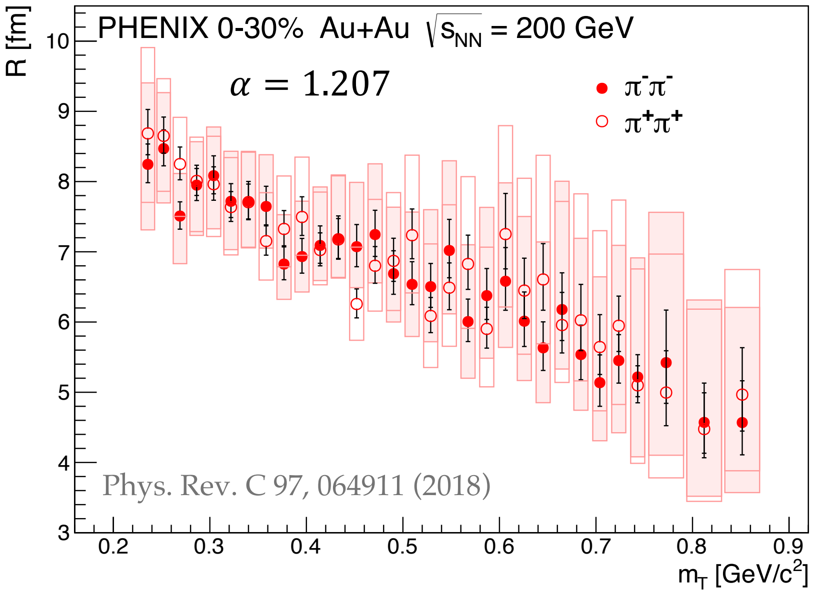


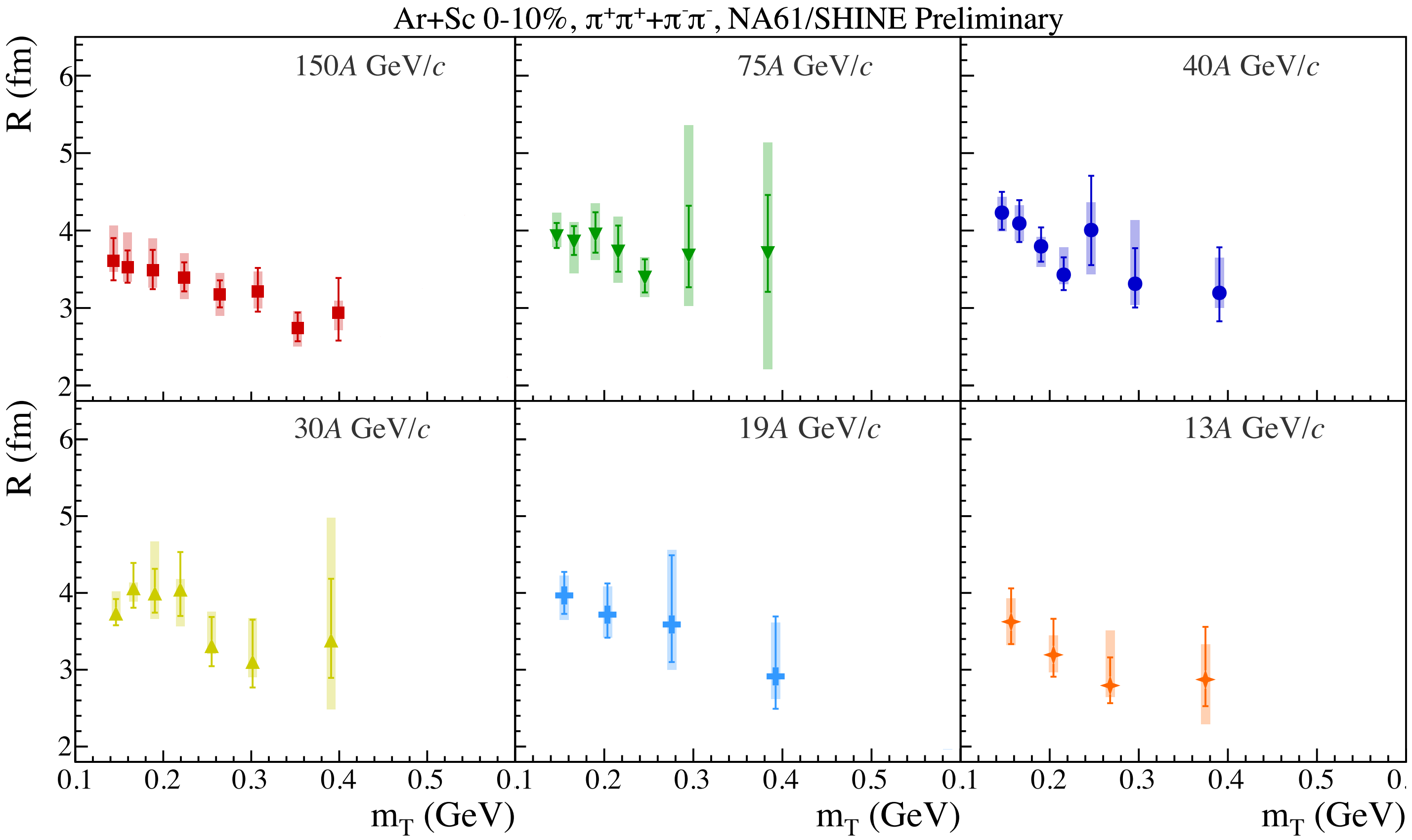
Energy dependence in ^{40}Ar+^{45}Sc

- For Gaussian sources $R \sim 1/\sqrt{m_T}$

Csörgő, Lörstad, Phys.Rev.C54 (1996) 1390

- Decreasing trend but $\alpha < 2$!
  - Present in other measurements as well



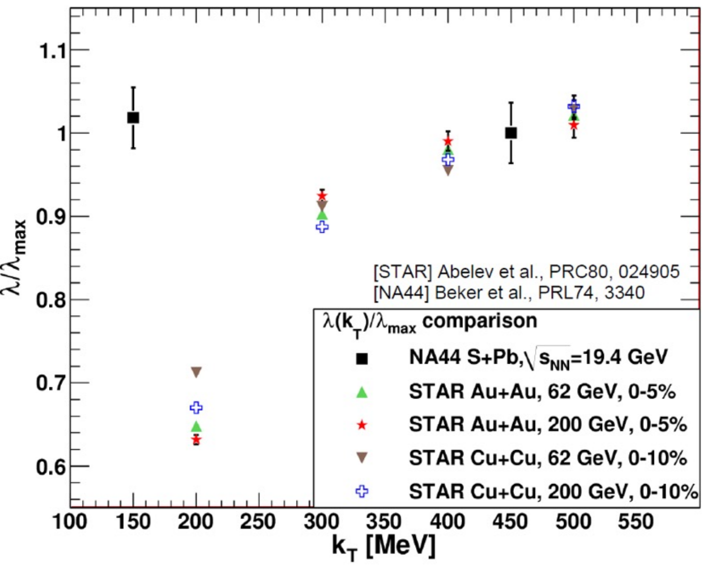


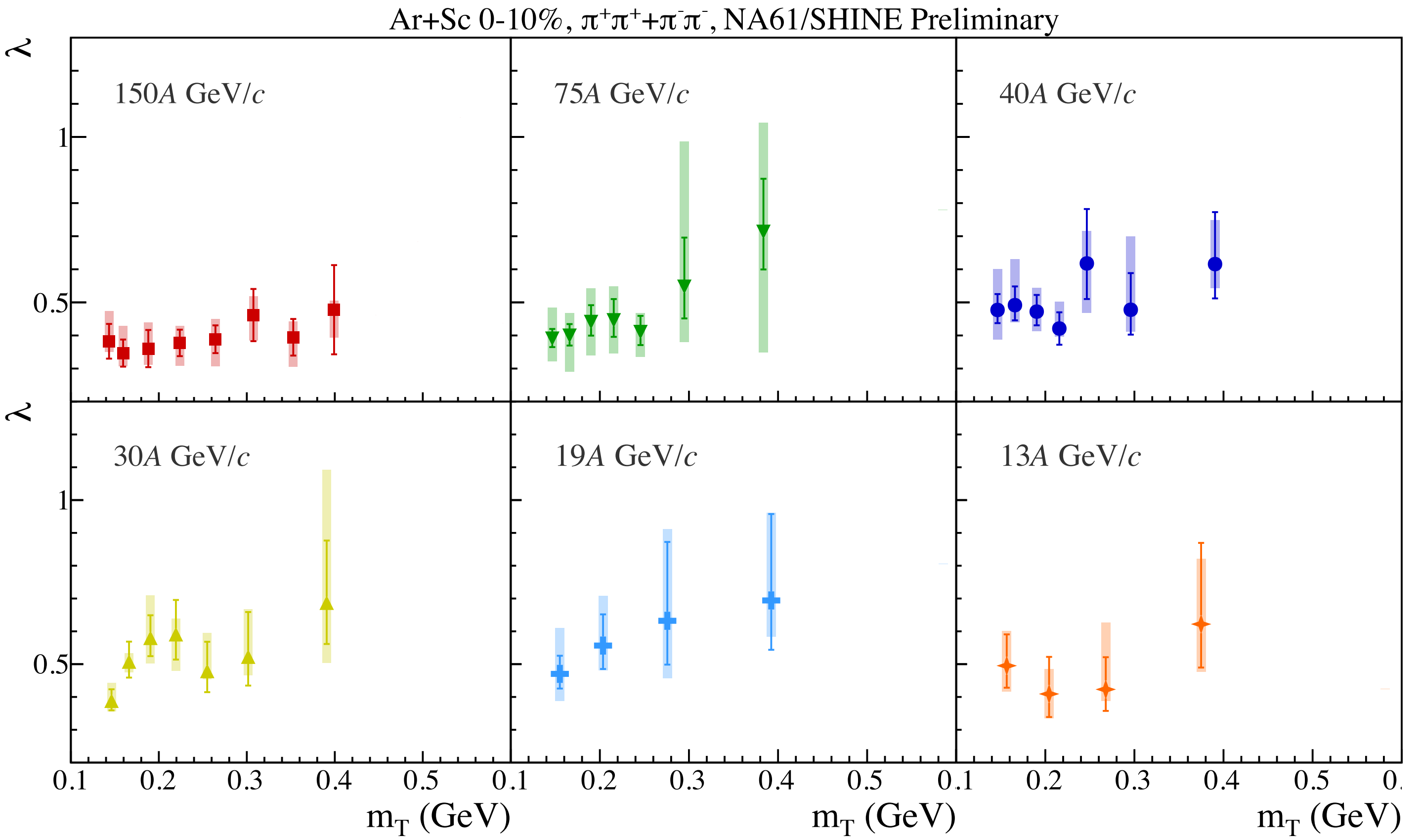
Energy dependence in ^{40}Ar+^{45}Sc

- Almost constant (except maybe 30*A* GeV/*c*)
- Halo component increases at RHIC; $\lambda = \left(\frac{N_{core}}{N_{core}+N_{halo}}\right)^2$

S. E. Vance et al, Phys.Rev.Lett. 81 (1998) 2205-2208
T. Csörgő et al, Phys.Rev.Lett. 105 (2010) 182301
A. Adare for PHENIX Collaboration, Phys.Rev. C97 (2018) no.6, 064911

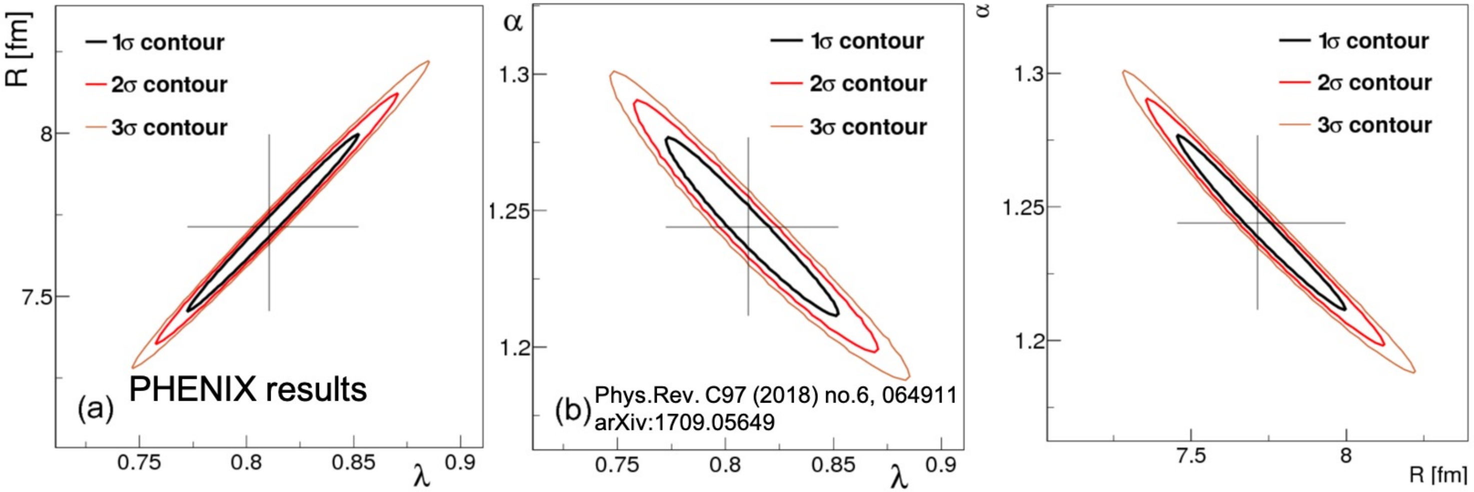
Not really visible at SPS





Interparameter correlation

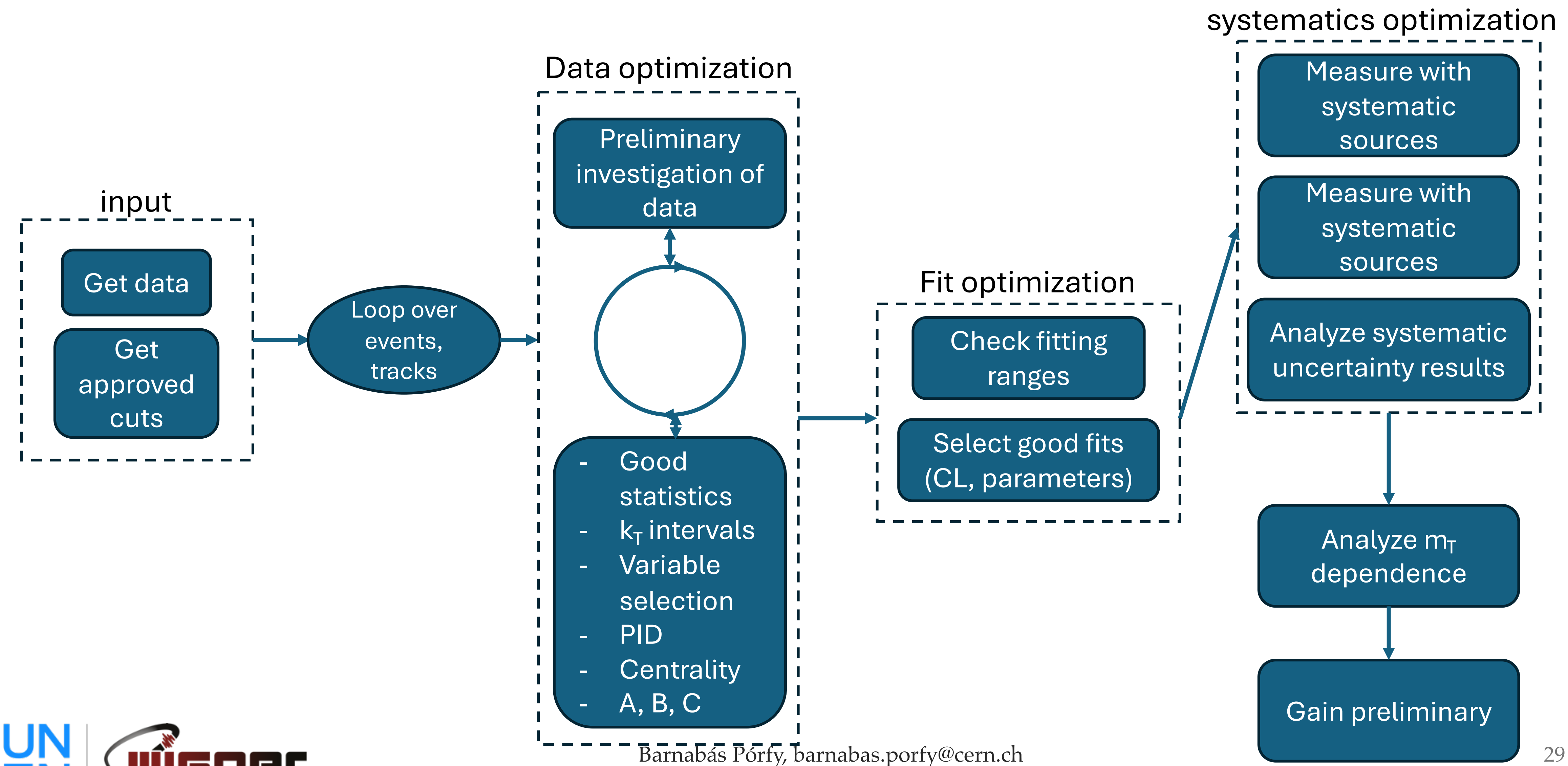
- Known characteristic of Lévy fit
- Observed in PHENIX, in NA61/SHINE
  - Statistical uncertainty: via Minos for 1σ contours
  - Statistical uncertainty of a given parameter:
    side length of "bounding box" of N-dimensional contour surface
  - 2D projections of N-dim. contour shown below
  - "Cross" shows parameter uncertainty, equal to contour projection
- To reduce the correlation – one parameter
  - α – approx. constant in m_T
  - R – m_T dependent fit, based on hydro
    $A/\sqrt{1+m_T/B}$



Calculation of Systematic Uncertainties

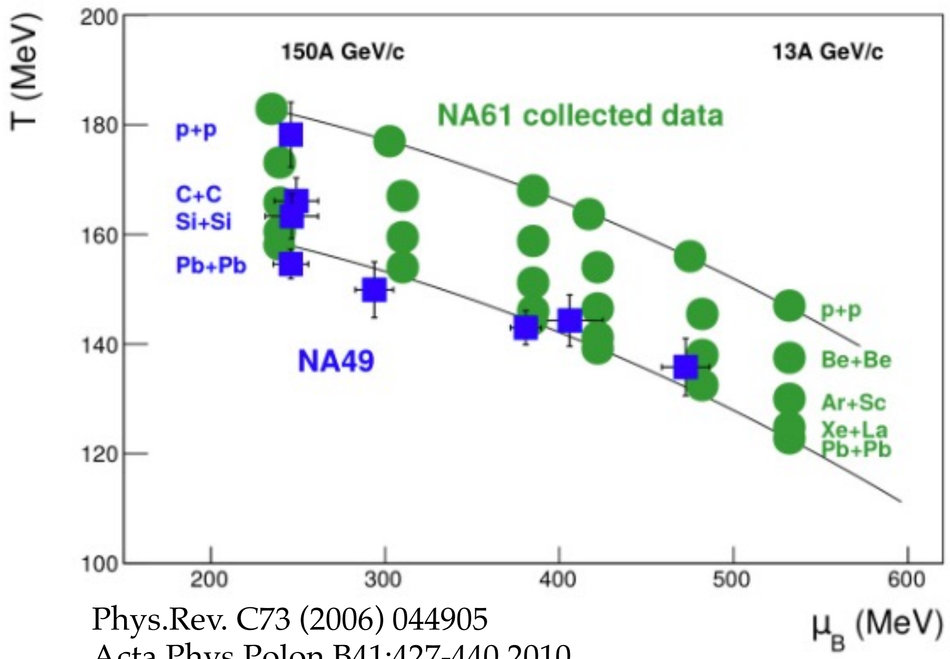
- $\delta P^{\pm}(i) = \sqrt{\sum_n \frac{1}{N_n^{j\pm}} \sum_{j \epsilon J_n^{\pm}} \left(P_n^j(i) - P^0(i)\right)^2}$
- Where:
  - i bin (0,1,2,3,…), in our case: K_T bins
  - $P^0(i)$ value of parameter in i
  - n # of systematic source
  - j option used: standard, loose or strict (0,1,2)

Analysis workflow



Further plans

- Finalization and article on ^{40}Ar+^{45}Sc energy scan results
- High multiplicity ^{129}Xe+^{139}La energy scan measurement
  - 3D, if possible

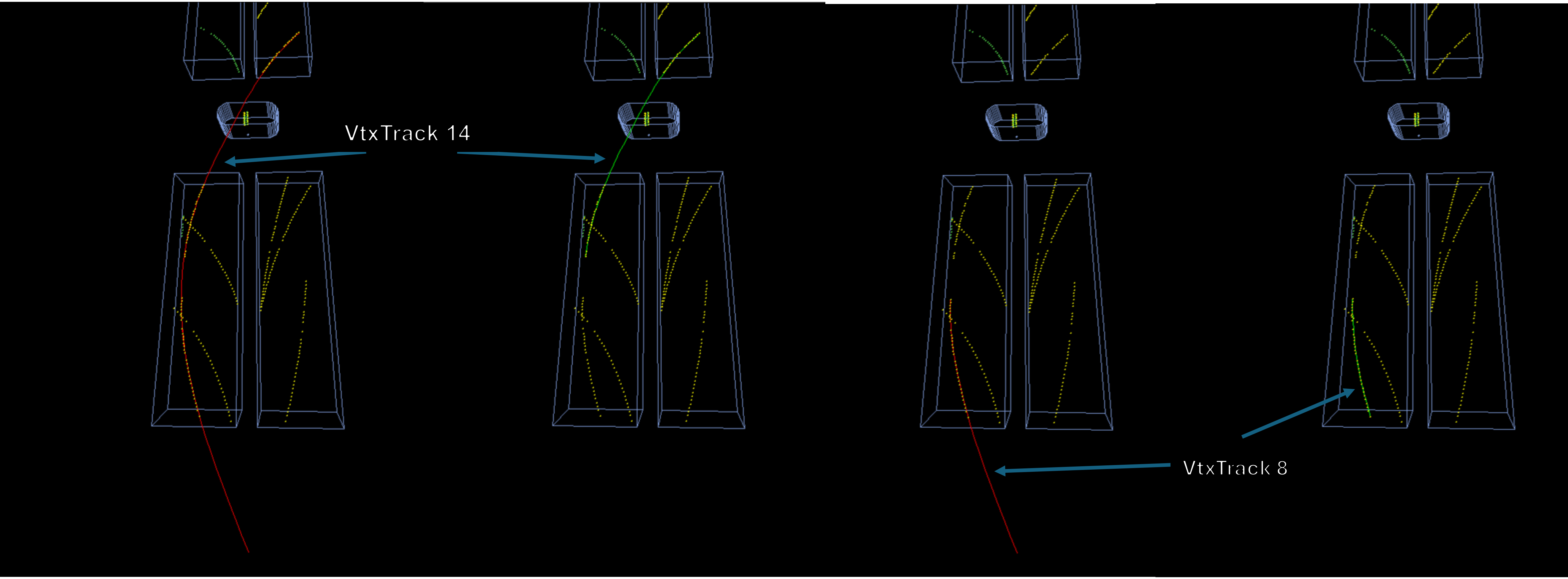


Phys.Rev. C73 (2006) 044905
Acta Phys.Polon.B41:427-440,2010

Thank you for your attention!

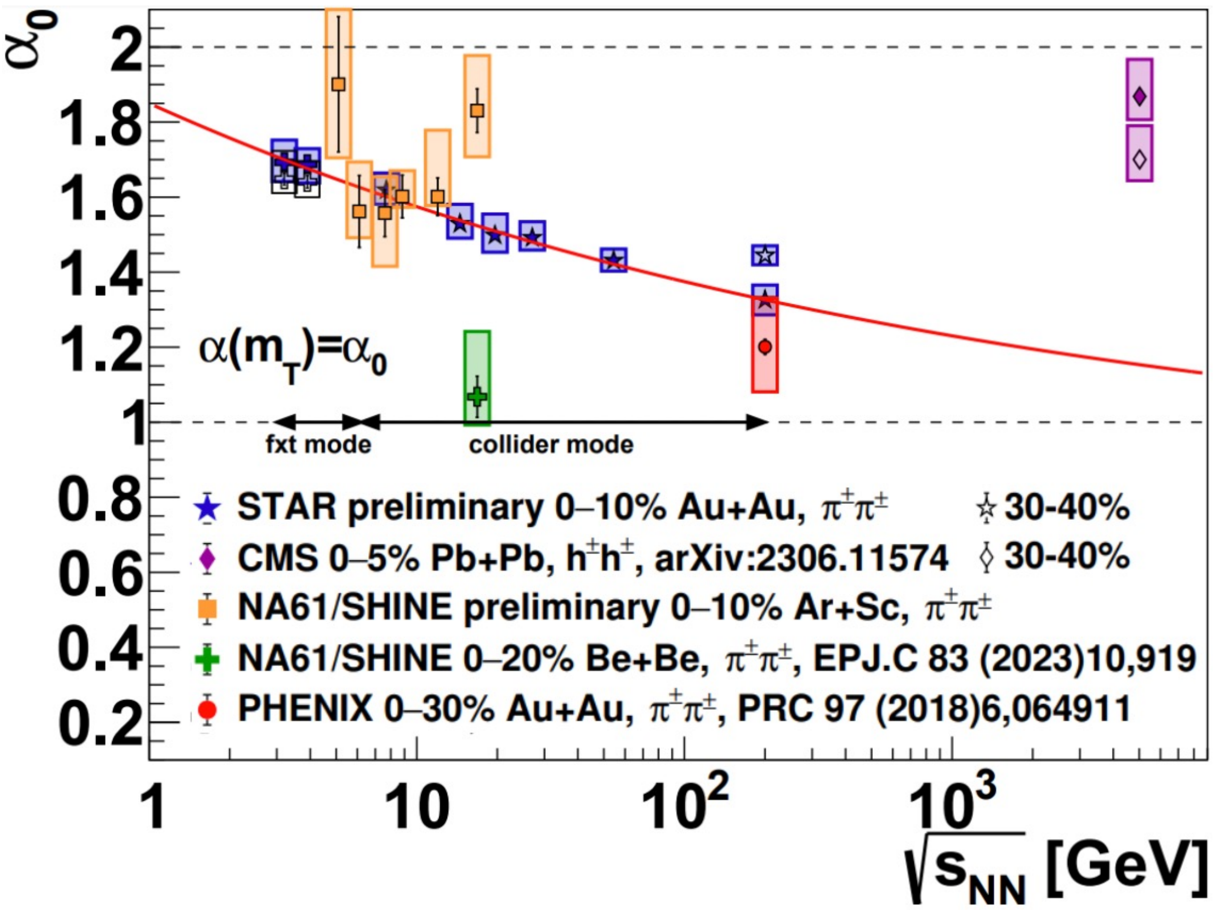
Backup

Split track



Femtoscopy group results

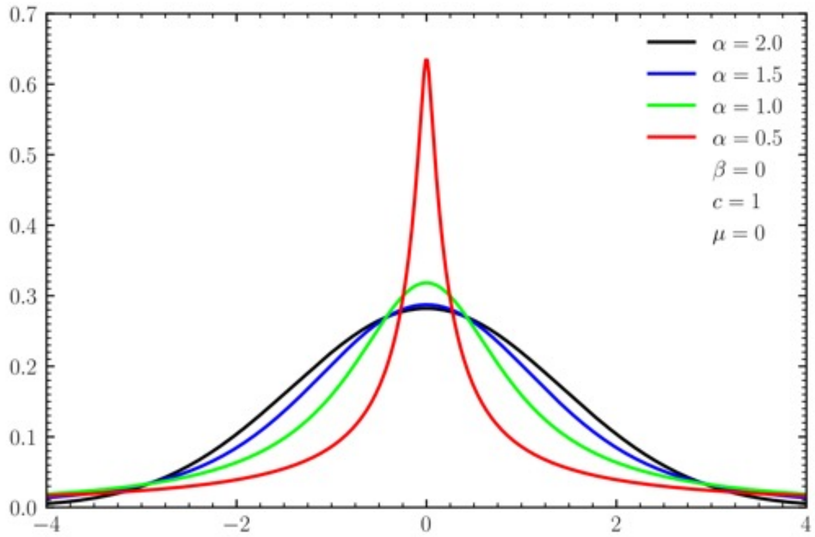
- Different experiments, different acceptances
- System size dependence?
- Centrality dependence?
- Energy dependence?



Stable distribution

- If a lin. comb. of two indep. random variables with this distribution has the same distribution
- $f(x) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\varphi(q)e^{-ixq}dq$, where the characteristic function:
- $\varphi(q;\alpha,\beta,R,\mu) = \exp(iq\mu - |Rq|^{\alpha}(1-\beta\,\mathrm{sgn}(q)\Phi)$
  α: stability index
  β: skewness, distribution is symmetric if $= 0$
  R: scale parameter
  μ: location parameter, if $\beta = 0 \rightarrow$ median

$$\Phi = \begin{cases} \tan\left(\frac{\pi\alpha}{2}\right), \alpha \neq 1 \\ -\frac{2}{\pi}\log|t|, \alpha = 1 \end{cases}$$



- Sum of two random variables from a stable distribution gives something with the same values of α and β (with possibly different values of μ, R …)
- Ha $\beta = 0 \Longrightarrow$ **Lévy symmetric alpha-stable distribution**